### 08-401

From Drorbn

### **Polynomial Equations and Fields**

### Department of Mathematics, University of Toronto, Spring 2008

**Agenda:** Follow Évariste Galois (http://en.wikipedia.org/wiki/Galois) to the top of mathematics' first mountain.

Classes: Wednesdays 6-9PM (OMG) at Sidney Smith 1086 (http://www.osm.ut oronto.ca/cgi-bin/class spec/spec03?bldg=SS&room=1086).

**Instructor:** Dror Bar-Natan (http://www.math.toronto.edu/~drorbn/), drorbn@math.toronto.edu, Bahen 6178, 416-946-5438. Office hours: by appointment.

**Teaching Assistant:** Yichao Zhang, zhangyichao2002@hotmail.com. Office hours: Tuesdays 1-3 at the Math Aid Centre, Sidney Smith 1071.

**Grades.** All grades will be on CCNet (http://ccnet.utoronto.ca/20081/mat401h1 s/).

### **Further Resources**

- J. Gallian's Algebra web site (http://www.d.umn.edu/~jgallian/).
- Undergraduate Information (http://www.math.toronto.edu/undergrad/) at the UofT Math Department (http://www.math.toronto.edu/)
- Undergraduate Course Descriptions (http://www.artsandscience.utoronto.ca/ofr/calendar/crs\_mat.htm) at the Faculty of Arts and Science (http://www.artsci.utoronto.ca/).
- Last year's class: 07-401.
- 06-401 (http://www.math.toronto.edu/gor/mat401.html) with Julia Gordon.
- 05-302 (http://www.math.utoronto.ca/shub/mat302S.html) with Mike Shub.
- 06-301 (http://ccnet.utoronto.ca/20069/mat301h1f/) with Lindsey Shorser.

08-401/Navigation Panel

#	Week of	Links
1	Jan 9	About, Notes, HW1
2	Jan 16	HW2, Notes
3	Jan 23	HW3, Photo, Notes
4	Jan 30	HW4, Notes
5	Feb 6	HW5, Notes
6	Feb 13	On TT, Notes
R	Feb 20	Reading week
7	Feb 27	Term Test (and solution)
8	Mar 5	HW6, Notes
9	Mar 12	HW7, Notes
10	Mar 19	HW8, Notes, RC (PDF)
11	Mar 26	HW9, Notes
12	Apr 2	FT, HW10, Notes
13	Apr 9	Notes
S	Apr 14-25	Study Period: blackboards (ht tp://katlas.math.toronto.edu/d rorbn/bbs/show?shot=08401- 080425-142418.jpg)
F	Apr 28	Final
	Add	your name / see who's in!

 $ln[1] = Solve[ax^4 + bx^3 + cx^2 + dx + e = 0, x] // First$ 

$$\begin{array}{l} \text{Out} \text{[1]= } \Big\{ x \to -\frac{b}{4 \, a} - \frac{1}{2} \, \sqrt{ \left( \frac{b^2}{4 \, a^2} - \frac{2 \, c}{3 \, a} + (2^{1/3} \, (c^2 - 3 \, b \, d + 12 \, a \, e) \, ) \, / \\ & \qquad \qquad \left( 3 \, a \, \left( 2 \, c^3 - 9 \, b \, c \, d + 27 \, a \, d^2 + 27 \, b^2 \, e - 72 \, a \, c \, e + \sqrt{ \left( -4 \, \left( c^2 - 3 \, b \, d + 12 \, a \, e \, \right)^3 \, + \frac{1}{3 \, 2^{1/3} \, a}} \right. \\ & \qquad \qquad \left( \left( 2 \, c^3 - 9 \, b \, c \, d + 27 \, a \, d^2 + 27 \, b^2 \, e - 72 \, a \, c \, e + \sqrt{ \left( -4 \, \left( c^2 - 3 \, b \, d + 12 \, a \, e \, \right)^3 \, + \frac{1}{3 \, 2^{1/3} \, a}} \right. \\ & \qquad \qquad \left( \left( 2 \, c^3 - 9 \, b \, c \, d + 27 \, a \, d^2 + 27 \, b^2 \, e - 72 \, a \, c \, e + \sqrt{ \left( -4 \, \left( c^2 - 3 \, b \, d + 12 \, a \, e \, \right)^3 \, + \frac{1}{3 \, 2^{1/3} \, a}} \right. \\ & \qquad \qquad \left( \left( 2 \, c^3 - 9 \, b \, c \, d + 27 \, a \, d^2 + 27 \, b^2 \, e - 72 \, a \, c \, e + \sqrt{ \left( -4 \, \left( c^2 - 3 \, b \, d + 12 \, a \, e \, \right)^3 \, + \frac{1}{3 \, 2^{1/3} \, a}} \right. \\ & \qquad \qquad \left( \left( 2 \, c^3 - 9 \, b \, c \, d + 27 \, a \, d^2 + 27 \, b^2 \, e - 72 \, a \, c \, e + \sqrt{ \left( -4 \, \left( c^2 - 3 \, b \, d + 12 \, a \, e \, \right)^3 \, + \frac{1}{3 \, 2^{1/3} \, a}} \right. \\ & \qquad \qquad \left( \left( 2 \, c^3 - 9 \, b \, c \, d + 27 \, a \, d^2 + 27 \, b^2 \, e - 72 \, a \, c \, e + \sqrt{ \left( -4 \, \left( c^2 - 3 \, b \, d + 12 \, a \, e \, \right)^3 \, + \frac{1}{3 \, 2^{1/3} \, a}} \right. \\ & \qquad \qquad \left( \left( 2 \, c^3 - 9 \, b \, c \, d + 27 \, a \, d^2 + 27 \, b^2 \, e - 72 \, a \, c \, e + \sqrt{ \left( -4 \, \left( c^2 - 3 \, b \, d + 12 \, a \, e \, \right)^3 \, + \frac{4 \, b \, c}{a^2} \, - \frac{8 \, d}{a^2}} \right) \right. \\ & \qquad \qquad \qquad \left. \left( \left( 2 \, c^3 - 9 \, b \, c \, d + 27 \, a \, d^2 + 27 \, b^2 \, e - 72 \, a \, c \, e \, + \sqrt{ \left( -4 \, \left( c^2 - 3 \, b \, d + 12 \, a \, e \, \right)^3 \, + \frac{1}{3 \, 2^{1/3} \, a}} \right. \right. \\ & \qquad \qquad \qquad \left. \left( \left( 2 \, c^3 - 9 \, b \, c \, d + 27 \, a \, d^2 + 27 \, b^2 \, e - 72 \, a \, c \, e \, + \sqrt{ \left( -4 \, \left( c^2 - 3 \, b \, d + 12 \, a \, e \, \right)^3 \, + \frac{1}{3 \, 2^{1/3} \, a}} \right. \right. \right. \right. \\ & \qquad \qquad \qquad \left. \left( \left( 2 \, c^3 - 9 \, b \, c \, d + 27 \, a \, d^2 + 27 \, b^2 \, e - 72 \, a \, c \, e \, + \sqrt{ \left( -4 \, \left( c^2 - 3 \, b \, d + 12 \, a \, e \, \right)^3 \, + \frac{1}{3 \, 2^{1/3} \, a}} \right. \right) \right. \right. \right. \right) \right) \right) \right) \right) \right) \right) \right) \right) \right\}$$

Solving The Quartic With Mathematica. Read more! (http://en.wikipedia.org/wiki/Quartic\_equation)

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This page was last edited on 10 April 2008, at 13:23.

Dror Bar-Natan: Classes: 2007-08: Math 401 Polynomials, Equations, Fields:

### Galois Theory Quick Reference

Goal. Some polynomials cannot be "solved" using  $+, -, \times, \div$ 

{field extensions}	The Fundamental  Theorem	{groups}
{extensions by roots}	$\longrightarrow$	{"solvable groups"}
splitting field of $3x^5 - 15x + 5$	$\longrightarrow$	the non-solvable permutation group $S_5$

#### To do.

- 1. More on splitting fields.
- 2. Quick reminders on group theory.
- 3. Precise statement of the fundamental theorem.
- 4. Examples for the fundamental theorem.
- 5. On solvable groups: definition, basic properties,  $S_5$  is not solvable.
- 6. "Extensions by radicals" correspond to solvable groups.
- 7. The splitting field of  $3x^5 15x + 5$  corresponds to  $S_5$ .
- 8. Proof of the fundamental theorem.

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The Fundamental Theorem of Galois Theory. Let F be a field of characteristic 0 and let E be a splitting field over F. Then there is a bijective correspondence between the set  $\{K: E/K/F\}$  of intermediate field extensions K lying between F and E and the set  $\{H: H < \operatorname{Gal}(E/F)\}$  of subgroups H of the Galois group  $\operatorname{Gal}(E/F)$  of the original extension E/F:

$$\{K: E/K/F\} \quad \leftrightarrow \quad \{H: H < \operatorname{Gal}(E/F)\}.$$

The bijection is given by mapping every intermediate extension K to the subgroup  $\operatorname{Gal}(E/K)$  of elements in  $\operatorname{Gal}(E/F)$  that preserve K,

$$\Phi: K \mapsto \operatorname{Gal}(E/K) := \{g : E \to E : g|_K = I\},\$$

and reversely, by mapping every subgroup H of  $\mathrm{Gal}(E/F)$  to its fixed field  $E_H$ :

$$\Psi: \ H \mapsto E_H := \{ x \in E : \forall h \in H, \ hx = x \}.$$

This correspondence has the following further properties:

- It is inclusion-reversing: if  $H_1 \subset H_2$  then  $E_{H_1} \supset E_{H_2}$  and if  $K_1 \subset K_2$  then  $\operatorname{Gal}(E/K_1) > \operatorname{Gal}(E/K_2)$ .
- It is degree/index respecting:  $[E:K] = |\operatorname{Gal}(E/K)|$  and  $[K:F] = [\operatorname{Gal}(E/F) : \operatorname{Gal}(E/K)].$
- Splitting fields correspond to normal subgroups: If K in E/K/F is the splitting field of a polynomial in F[x] then Gal(E/K) is normal in Gal(E/F) and  $Gal(K/F) \cong Gal(E/F)/Gal(E/K)$ .

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# UNIVERSITY OF TORONTO Faculty of Arts and Sciences FINAL EXAMINATIONS, APRIL-MAY 2008 Math 401H1S Polynomial Equations and Fields

Instructor: Dror Bar-Natan Date: April 28, 2008

**Duration.** You have 3 hours to write this exam.

Allowed Material. Basic calculators, not capable of displaying text or sounding speech.

Solve 6 of the following 7 questions. Each question is worth 17 points, to a maximum possible total of 102. Different parts of the same question may be weighted differently. You will get 4 points total for any problem for which you will write explicitly "I don't know how to solve this problem" (whole problems only!).

Neatness counts! Language counts! The *ideal* written solution to a problem looks like a proof from the textbook; neat and clean and made of complete and grammatical sentences. Definitely phrases like "there exists" or "for every" cannot be skipped. Lectures are mostly made of spoken words, and so the blackboard part of proofs given during lectures often omits or shortens key phrases. The ideal written solution to a problem does not do that.

Good Luck!

### Solve 6 of the following 7 problems. Neatness counts! Language counts!

<b>Problem 1.</b> Let $R$ be a commutative ring with unity and let $A$ be an ideal of $R$ . Define "A is prime" and "a ring $D$ is a domain" and prove that $D := R/A$ is a domain if and of if $A$ is prime.  Tip. The phrase "if and only if" means that there are two things to prove.  The definition of a "problem" is a domain.	
<b>Problem 2.</b> Let $\mathbb{Q}$ be the ring of rational numbers and let $\mathbb{Z}$ be the ring of integers. Is there a ring $S$ and a ring homomorphism $\phi: \mathbb{Q} \to S$ so that $\ker \phi = \mathbb{Z}$ ?  152. Is there a ring $S$ and a ring homomorphism $\psi: \mathbb{Q} \to S$ so that im $\psi$ is isomorphic $\mathbb{Z}$ ?  2 for where $\psi: \mathbb{Q} \to S$ so that $\psi: \mathbb{Q} \to S$ so that $\mathcal{C} \to S$ is isomorphic $\mathcal{C} \to S$ ?  2 for where $\mathcal{C} \to S$ is the ring of integers.	
whatever they are.  Problem 3. Let $F$ be a field, $A$ a non-zero ideal in $F[x]$ , and $g \in F[x]$ a polynom Prove that $A = \langle g \rangle$ if and only if $g$ is a non-zero polynomial of minimal degree in $A$ .  Tip. As always in math exams, when proving a theorem you may freely assume anything that precede but you may not assume anything that followed it.	ial.
<b>Problem 4.</b> Is it always true that a splitting extension of a splitting extension is a splitt extension? In other words, let $F$ be a field, $f \in F[x]$ be a polynomial with coefficients $F$ , $K$ be a splitting field of $f$ over $F$ , $g \in K[x]$ be a polynomial with coefficients in $K$ , a $E$ be a splitting field of $g$ over $K$ . Is it always the case that there is a polynomial $h \in F$ with coefficients in $F$ so that $E$ is a splitting field of $h$ over $F$ ?  Tip. This, of course, is also not just a yes/no question. Whatever you state, you have to prove, unless is a known earlier result.  The property of the splitting field of $f$ and $f$ and $f$ and $f$ and $f$ and $f$ and $f$ are $f$ are $f$ and $f$ are $f$ are $f$ and $f$ are $f$	x in and $x$ in $x$

**Problem 5.** Let E/F be a field extension, and let  $a_k$  (for  $0 \le k \le n$ ) be elements of E that are algebraic over F. Let b be some solution in E of the equation  $\sum_{k=0}^{n} a_k b^k = 0$ . Prove that b is also algebraic over F.

10 SI

**Problem 6.** For any group A, recall that [A, A], the commutator group of A, is the subgroup of A generated by all elements of the form  $[x, y] := xyx^{-1}y^{-1}$ , where  $x, y \in A$ .

 $7 \cancel{1}$ 1. Let G be a group. Define "G is solvable".

 $\nearrow$  2. For any group H, prove that if  $H' \triangleleft H$  is a normal subgroup, if H/H' is Abelian and if A < H is some other subgroup, then [A, A] < H'.

3. Prove that if a group G contains a non-trivial subgroup A for which [A, A] = A, then G is not solvable.



**Problem 7.** Let F be the field  $\mathbb{Q}(i)$  (note that F is not  $\mathbb{Q}$ !) and let E be the field  $\mathbb{Q}(\sqrt[4]{2}, i)$ .

 $\bigcirc$  1. Compute G := Gal(E/F).

 $5 \ / \ 2$ . Find all the subgroups H of G.

3. For exactly one non-trivial proper subgroup of G (that is, a subgroup that is neither  $\{e\}$  nor G), describe the fixed field  $E_H$ .

**Tip.** The word "describe" here means "find  $a \in E$  so that  $E_H = F(a)$ ".

### Good Luck!

### Faculty of Arts & Science University of Toronto Survey Summary Results: SPR 08

Course:

MAT 401H1S

Enrolment:

Section: L5101

STATEMENTS ABOUT THE INSTRUCTOR:

Number of Forms Scanned: 15

Instructor: D. BAR-NATAN

#### STATEMENTS ABOUT THE COURSE:

Quest.	%	Res	p. t	o Sc	ale	Rati	ng	No.	Mean	Quest.	%	Resp	). t	o Sc	ale	Rati	ng	No.	Mean
	1	2	3	4	5	6	7				1	2	3	4	5	6	7		
		1											_						-
2.	0	0	0	6	60	20	13	15	5.4	12.	0	0	0	33	26	26	13	15	5.2
3.	0	0	20	26	26	20	6	15	4.7	13.	0	0	0	13	13	60	13	15	5.7
4.	0	0	0	20	53	13	13	15	5.2	14.	0	0	7	23	30	38	0	13	5.0
5.	0	0	6	26	33	20	13	15	5.1	15.	0	0	0	33	0	66	0	3	5.3
6.	0	0	0	0	28	50	21	14	5.9	16.	0	0	0	33	0	66	0	3	5.3
7.	0	0	0	21	35	28	14	14	5.4	17.	0	0	0	50	0	50	0	2	5.0
8.	0	0	0	8	50	16	25	12	5.6	18.	0	0	0	40	20	40	0	5	5.0
9.	0	0	7	35	28	21	7	14	4.9	19.	0	0	7	28	35	28	0	14	4.9
10.	0	0	0	6	26	26	40	15	6.0										
11.	0	0	0	7	42	21	28	14	5.7	20.	Yes	3: 5	08	No	: 5	0%		14	

#### OTHER QUESTIONS:

Quest.	%	Resp	. to	Sca	ale	Rati	ng	No.	Mean	Quest.	왕	Resp	. to	Sca	ale	Ratin	<u>ıg</u>	No.	Mean
	1	2	3	4	5	6	7				1	2	3	4	5	6	7		
25.	0	0	0	0	0	0	0	0	0.0	31.	0	0	0	0	0	0	0	0	0.0
26.	0	0	0	0	0	0	0	0	0.0	32.	0	0	0	0	0	0	0	0	0.0
27.	0	0	0	0	0	0	0	0	0.0	33.	0	0	0	0	0	0	0	0	0.0
28.	0	0	0	0	0	0	0	0	0.0	34.	0	0	0	0	0	0	0	0	0.0
29.	0	0	0	0	0	0	0	0	0.0	35.	0	0	0	0	0	0	0	0	0.0
30.	0	0	0	0	0	0	0	0	0.0	36.	0	0	0	0	0	0	0	0	0.0

#### MEAN RATING ON QUESTION 11 (GLOBAL EVALUATION OF INSTRUCTOR) AS A FUNCTION OF STUDENT INFORMATION:

		No.	Mean Global Eval.
21.	Number of full courses already completed:		
	0- 4.5	0	=
	5- 9.5	0	-
	10-14.5	4	5.8
	15-19.5	8	5.9
	>=20	2	5.0
22.	Status of the course for the student:		
	Program Requirement	9	6.1
	Selected from a required list in a program	3	4.7
	Breadth requirement	0	¥
	Optional	0	*
23.	Initial enthusiasm to take course:		
		-	
	low	3	5.3
	medium	6	5.7
	high	3	6.0
24.	Expected grade in course:		
	<50	0	×
	50-59	2	4.5
	60-69	3	5.0
	70-79	6	6.3
	80-89	1	6.0
	>=90	0	, <u> </u>



Note that survey results will be available to the instructor(s) only after final course marks have been submitted.

1 vote that but vey results will be available to the most most (e)							
PART I: INSTRUCTIONS. PLEASE READ FIRST.							
		1.	\ 011	1 1 1	1	1 1	
Using an HB pencil or a blue or black ball-point pen (but not a for corresponding to your response for each statement. If using a pen,							ion.
Part II (on the reverse side) requires a written answer.							
Course Identification: Please print course and section you are evaluate	ing						
		7					
COURSE MAT401 SECTION / 01	0			INSTR	RUCTOR	(S):	
1. If evaluating only one instructor, write the name in the upper (A) box. two instructors, write their names, one in box A and the other in box E	lf evalu 3.	uating	A: B:	Bar	Nan		
DO NOT EVALUATE TEACHING ASSISTANTS ON THIS FO	RM		В.				
Respond to the statements below for instructor A (and instructor B) and subject matter in Arts and Science.	bearin		nd that th			very	outstanding
2. Communicates goals and requirements of the course clearly	poo	or po	oór		0	good	
and explicitly.	A: 1		2) 3	4	<b>19</b>	6	(7)
3. Uses methods of evaluation (e.g. papers, assignments, tests) that appropriately reflect the subject matter and provide a fair evaluation	B: 1		2) (3)	4)	• (		<i>•</i>
of student learning	. A: 1 B: 1	) (	2 3	4	(5)	6	(7)
	Б. 🕕		2) (3)	4			
4. Presents material in an organized, well-planned manner	A: 1		2 3		@/	6	7)
	B: ①	) (	2) (3)	(4)	(5)	(6)	
5. Explains concepts clearly with appropriate use of examples			2) 3		82/	6	(7)
	B: 🚺	) (	2) 3	4	(5)	6	7
6. Communicates enthusiasm and interest in the course material	A: 1	) (	2) (3)		10/	6	(7)
	B: 💶	) (	2) 3	4	(5)	6	(7)
7. Attends to students' questions and answers them clearly and effectively.	. A: 1		2) (3)	4	is	6	7
-	B: 1	) (	2) (3)	4	(5)	6	(7)
Is available for individual consultation, by appointment or stated office hours, to students with problems relating to the course	. A: 1	) (	2 3	4	(E)	6	7
	B: 1		2) (3)		5	6	(7)
Ensures that student work is graded fairly, with helpful comments     and feedback where appropriate	Δ. 🗇		2) (3)	4	<b>6</b>	6	(7)
ани невираск where арргорнате	B: 1		2) (3)		5	6	(7)
10. Ensures that student work is graded within a reasonable time	. A: 1		2) (3)	4	VS	6	(7)
10. Ensures that student work is graded within a reasonable time	B: 1		2) (3)		(5)	6	(7)
11. All things considered, performs effectively as a university teacher	A		2) (3)	4	(See)	6	(7)
44 All this are new side und monte una effectively as a conjugative teacher							

	nents about the course	e: Respond to the st	atements below	using the	follow	ing 7-poi	nt scale.		S	IDE 2
2 Con	monard to other courses at t	No I (400 00	0.000.400\ .1	very low	low	below	average	above	high	very high
	npared to other courses at t			· (1)	(2)	3	4)	(5)	2	7
3. Con	npared to other courses at t	the same level, the lev	el of difficulty of		2	(3)	4	5		
the	material is			<b>(1</b> )	(2)	(3)	4	(5)	8	(7)
4. The	value of the required reading	ng is		. 1	2	(3)	4	(5)	40/	(7)
5. (If a	pplicable) The value of the	tutorials is		. 1	(2)	3	4	(5)	9	(7)
	pplicable) The value of the				(2)	(3)	(4)	(5)	·	(7)
	pplicable) The value of the				(2)	3	(4)	(5)	18	(7)
	pplicable) The value of the				(2)	(3)	4	5	3	(7)
	value of the overall learning				(2)	(3)	(4)	5	0	7
mee	nsidering your experience w et program or degree require	ements, would you sti	sregarding your Il have taken this	course?	το	Ye	5	O No		
3. You 1. You	Program Requirement ur level of enthusiasm to tak low 2 medium ur expected grade in this col <50 2 50-59	🞾 high	quired list in a pro ne of initial regis	gram tration:		eadth Requ	uirement	4	Optional	
	ional statements or qu	estions which m	ay be supplie	d in clas	s:					
dditi						5 6 7		34. 🕦	2 (3) (4)	
5. 1	2 3 4 5 6 7	<b>28.</b> (1) (2) (3) (4) (5)	(6) (7)	31. <u>1</u>	2 3 4					5 (6) (7
25. <u>1</u>		28. (1) (2) (3) (4) (5) (29. (1) (2) (3) (4) (5) (5) (30. (1) (2) (3) (4) (5)	(6) (7)	32. 🕕 🤇	2 (3) (4)			35. 🕦		5 6 7 5 6 7





Note that survey results will be available to the instructor(s) only after final course marks have been submitted.

### PART I: INSTRUCTIONS. PLEASE READ FIRST. Using an HB pencil or a blue or black ball-point pen (but not a felt marking pen), fill completely the numbered oval corresponding to your response for each statement. If using a pen, do not alter original response by making another selection. Part II (on the reverse side) requires a written answer. Course Identification: Please print course and section you are evaluating **SECTION INSTRUCTOR(S):** COURSE | A: Bar Natan 1. If evaluating only one instructor, write the name in the upper (A) box. If evaluating two instructors, write their names, one in box A and the other in box B. B: DO NOT EVALUATE TEACHING ASSISTANTS ON THIS FORM Statements about the instructor(s): Respond to the statements below for instructor A (and instructor B) bearing in mind that there are wide variations in class size and subject matter in Arts and Science. outstanding extremely very adequate poor 2. Communicates goals and requirements of the course clearly 3. Uses methods of evaluation (e.g. papers, assignments, tests) that appropriately reflect the subject matter and provide a fair evaluation 4. Presents material in an organized, well-planned manner. . . . . . 1 6. Communicates enthusiasm and interest in the course material. . . . . . A: 1 7. Attends to students' questions and answers them clearly A: 1 and effectively. . . . . 8. Is available for individual consultation, by appointment or stated office hours, to students with problems relating to the course. . . A: 1 6 B: 1 9. Ensures that student work is graded fairly, with helpful comments 6 A: 💶 2 B: (1 A: 1 10. Ensures that student work is graded within a reasonable time. . . . . . B: 1 11. All things considered, performs effectively as a university teacher. ... A: 1

Statements about the course: Respond to the statements below,	using the	e follow	ing 7-poi	nt scale.			SIDE 2
	very low	low	below average	average	above	high	very high
12. Compared to other courses at the same level (100,200,300,400), the					average		
work load is	1	2	3	4	•	6	7
the material is	1	(2)	3		(5)	6	7
4. The value of the required reading is	1	(2)	(3)	(4)	(5)	(6)	7
5. (If applicable) The value of the tutorials is	(1)	(2)	(3)	4	(5)	(6)	7
6. (If applicable) The value of the laboratories is		(2)	(3)	4	(5)	6	(7)
7. (If applicable) The value of the seminars is	(1)	(2)	(3)	4	(5)	(6)	(7)
8. (If applicable) The value of the language conversation classes is	(1)	(2)	(3)	0	(5)	(6)	(7)
9. The value of the overall learning experience is		(2)	(3)	6	(5)	6	(7)
meet program or degree requirements, would you still have taken this of statements about yourself:			◯ Ye		<b>●</b> N		
1 $0-4\frac{1}{2}$ 2 $5-9\frac{1}{2}$ 6 $10-14\frac{1}{2}$ 4 $15-19\frac{1}{2}$	(5)	≥20					
1) 0-41/2 (2) 5-91/2 (3) 10-141/2 (4) 15-191/2 2. Status of the course for you:  1) Program Requirement Selected from a required list in a program Requirement	ram		eadth Req	uirement	(4	DOptiona	I
1) 0-4½ 2) 5-9½ 3) 10-14½ 4) 15-19½ 2) Status of the course for you: 1) Program Requirement 2) Selected from a required list in a prog 3) Your level of enthusiasm to take this course at the time of initial registress of the program	ram		eadth Req	uirement	(4	D Optiona	I
10-41/2 2 5-91/2 10-141/2 4 15-191/2  22. Status of the course for you: 1 Program Requirement Selected from a required list in a prog  33. Your level of enthusiasm to take this course at the time of initial registred library in the second of the second o	ram		eadth Reqi	uirement	(4	D Optiona	I
1) 0-4½ 2) 5-9½ 3) 10-14½ 4) 15-19½ 2) Status of the course for you: 1) Program Requirement 2) Selected from a required list in a prog 3) Your level of enthusiasm to take this course at the time of initial registress of the program	ram	③ Br	eadth Reqi	uirement	(4	DOptiona	ı
2. Status of the course for you: 1 Program Requirement Selected from a required list in a prog 3. Your level of enthusiasm to take this course at the time of initial registred list. 1 low Medium Mour expected grade in this course: 1 <50 50-59 3 60-69 4 70-79  Additional statements or questions which may be supplied	ram ration:	3 Br ≥80					
2. Status of the course for you: 1 Program Requirement Selected from a required list in a prog 2. Your level of enthusiasm to take this course at the time of initial registred list. 1 low Medium Med	ram (5) in clas 31. (1)	3 Br ≥80	(5) (6) (7)		34. 🛽	2 3 4	() (5) (6) (7)
2. Status of the course for you:  1 Program Requirement Selected from a required list in a prog  3. Your level of enthusiasm to take this course at the time of initial registred list.  1 low Medium	ram (5) (1) (1) (32) (1)	(3) Br ≥80 2) (3) (4) 2) (3) (4)	(5) (6) (7) (5) (6) (7)		34. 1 35. 1	2 3 4 2 3 4	1) (5) (6) (7) 1) (5) (6) (7)
22. Status of the course for you:  1 Program Requirement Selected from a required list in a prog 23. Your level of enthusiasm to take this course at the time of initial registre in low medium high 24. Your expected grade in this course:  1 <50 50-59 3 60-69 4 70-79  Additional statements or questions which may be supplied 25. 1 2 3 4 5 6 7	ram (5) (1) (1) (32) (1)	(3) Br ≥80 2) (3) (4) 2) (3) (4)	(5) (6) (7)		34. 1 35. 1	2 3 4	D (5) (6) (7 D (5) (6) (7



Note that survey results will be available to the instructor(s) only after final course marks have been submitted.

PART I: INSTRUCTIONS. PLEASE READ FIRST.  Using an HB pencil or a blue or black ball-point pen (but not a corresponding to your response for each statement. If using a pen	elt marking						
	elt markins						
		g nen), f	ill come	letely the	number	ed oval	
							ion.
Part II (on the reverse side) requires a written answer.							
Course Identification: Please print course and section you are evalua	ting						
7	8						
COURSE MATUOI SECTION				INSTRU	JCTOR(	(S):	
1. If evaluating only one instructor, write the name in the upper (A) box.	If evaluating	g A:	Dron				
two instructors, write their names, one in box A and the other in box	В.	B:					
DO NOT EVALUATE TEACHING ASSISTANTS ON THIS FO	ORM						
Statements about the instructor(s):							
Respond to the statements below for instructor A (and instructor B	bearing in	mind t	hat there	e are wide	variatio	ns in cla	ıss size
and subject matter in Arts and Science.	8						
and subject matter in this and obtained				adequate	good	MOSA	outstandin
	extremely poor	very	poor	adequate	good	good	outstanding
Communicates goals and requirements of the course clearly	A · (1)	(2)	(3)	(4)	(5)	6	
Communicates goals and requirements of the course clearly and explicitly.	. A: 1 B: 1	2	3	(4) (4)	( <u>5</u> )	6	7
and explicitly	. A: 1 B: 1						7
and explicitly.	B: 1	2	3	4	5	6	7
and explicitly	B: 1	(2)	(3)	4	(5)	(6)	7
and explicitly.  3. Uses methods of evaluation (e.g. papers, assignments, tests) that appropriately reflect the subject matter and provide a fair evaluation of student learning.	B: 1  . A: 1  B: 1	2	3	4	5	6	7
and explicitly	B: 1  . A: 1  B: 1	2 2	(3) (3)	4	(5) (5)	6	7
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and explicitly.  3. Uses methods of evaluation (e.g. papers, assignments, tests) that appropriately reflect the subject matter and provide a fair evaluation of student learning.	B: 1  . A: 1  B: 1  . A: 1  B: 1	(2) (2) (2) (2)	3 3 3 3	(4) (4) (4) (4)	(5) (5) (5) (5)	6 6 6 6	7
<ol> <li>Uses methods of evaluation (e.g. papers, assignments, tests) that appropriately reflect the subject matter and provide a fair evaluation of student learning.</li> <li>Presents material in an organized, well-planned manner.</li> <li>Explains concepts clearly with appropriate use of examples.</li> </ol>	B: 1  . A: 1  B: 1  . A: 1  B: 1  . A: 1  B: 1	(2) (2) (2) (2) (2) (2)	3 3 3 3 3 3	(4) (4) (4) (4)	(5) (5) (5) (5) (5)	6 6 6 6	
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<ol> <li>Uses methods of evaluation (e.g. papers, assignments, tests) that appropriately reflect the subject matter and provide a fair evaluation of student learning.</li> <li>Presents material in an organized, well-planned manner.</li> <li>Explains concepts clearly with appropriate use of examples.</li> <li>Communicates enthusiasm and interest in the course material.</li> </ol>	B: 1  . A: 1  . A: 1  . A: 1	(2) (2) (2) (2) (2) (2) (2)	(3) (3) (3) (3) (3) (3)	4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4	(5) (5) (5) (5) (5) (5)	(6) (6) (6) (6) (6) (6)	
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atements about the course: Respond to the statements bel	ow, using the	e follow	ing 7-poi	nt scale.		3	SIDE 2
Compared to other courses at the core level (400 000 000 400) It.	very low	low	below average	average	above average	high	very high
. Compared to other courses at the same level (100,200,300,400), the work load is		2	(3)		(5)	6	7
. Compared to other courses at the same level, the level of difficulty	of	(2)	(3)		5	0	0
the material is	(1)	2	(3)		(5)	6	(7)
. The value of the required reading is	①	(2)	(3)	4	(5)		(7)
. (If applicable) The value of the tutorials is	1	(2)	(3)	(4)	(5)	6	(7)
(If applicable) The value of the laboratories is	1	2	(3)	(4)	(5)	6	(7)
(If applicable) The value of the seminars is	👲	(2)	(3)	4	(5)	(6)	(7)
. (If applicable) The value of the language conversation classes is	👲	(2)	3	4	5	(6)	(7)
The value of the overall learning experience is		(2)	(3)	4	(5)		(7)
atements about yourself:  Number of full course credits already earned (prior to this session 1 0-41/2 2 5-91/2 3 10-141/2 15-19  Status of the course for you:  Program Requirement 2 Selected from a required list in a Your level of enthusiasm to take this course at the time of initial re	his course?	≥20	Ye readth Req		○ No	Optional	
atements about yourself:  Number of full course credits already earned (prior to this session 1 0-4½ 2 5-9½ 3 10-14½ 15-19  Status of the course for you:  Program Requirement 2 Selected from a required list in a your level of enthusiasm to take this course at the time of initial re 1 low 2 medium high  Your expected grade in this course:	his course?  : 2 5  program gistration:	≥20 ③ B				Optional	
meet program or degree requirements, would you still have taken to atements about yourself:  Number of full course credits already earned (prior to this session 1 0-4½ 2 5-9½ 3 10-14½ 15-19  Status of the course for you:  Program Requirement 2 Selected from a required list in a your level of enthusiasm to take this course at the time of initial region of the course at the time of the course at the course at the time of the course at the time of the course at the time of the course at	his course?  : 2 5  program gistration:	≥20				Optional	
atements about yourself:  Number of full course credits already earned (prior to this session 1 0-4½ 2 5-9½ 3 10-14½ 15-19  Status of the course for you:  Program Requirement 2 Selected from a required list in a your level of enthusiasm to take this course at the time of initial re 1 low 2 medium high  Your expected grade in this course:  1 <50 2 50-59 3 60-69 70-79	his course?  : 2 5  program gistration:	≥20 ③ B ≥80				Optional	
atements about yourself:  Number of full course credits already earned (prior to this session 1 0-4½ 2 5-9½ 3 10-14½ 15-19  Status of the course for you:  Program Requirement 2 Selected from a required list in a your level of enthusiasm to take this course at the time of initial received in this course:  Your expected grade in this course:    Solution   Solutio	tied in clas	≥20 ③ B ≥80 SS:	readth Req			Optional	(5)(6)(7
atements about yourself:  Number of full course credits already earned (prior to this session 1 0-4½ 2 5-9½ 3 10-14½ 15-19  Status of the course for you:  Program Requirement 2 Selected from a required list in a your level of enthusiasm to take this course at the time of initial re high  Your expected grade in this course:  1 <50 2 50-59 3 60-69 70-79	orogram gistration:  (5)  (6)  (6)  (6)  (7)  (7)  (7)  (8)	≥20 3 B ≥80 88: 2 3 4 4 2 3 4	readth Req		4	(2) (3) (4 (2) (3) (4	(5) (6) (1 (5) (6) (7





**INSTRUCTOR(S):** 

A: Dror Bac-Natan

B:

Note that survey results will be available to the instructor(s) only after final course marks have been submitted.

### PART I: INSTRUCTIONS. PLEASE READ FIRST.

Using an HB pencil or a blue or black ball-point pen (but not a felt marking pen), fill completely the numbered oval corresponding to your response for each statement. If using a pen, do not alter original response by making another selection.

**SECTION** 

Part II (on the reverse side) requires a written answer.

**COURSE** 

Course Identification: Please print course and section you are evaluating

1. If evaluating only one instructor, write the name in the upper (A) box. If evaluating two instructors, write their names, one in box A and the other in box B.

DO NOT EVALUATE TEACHING ASSISTANTS ON THIS FORM

11. All things considered, performs effectively as a university teacher. . . A: 1

Sta	tements about the instructor(s):								
	spond to the statements below for instructor A (and instructor B) I subject matter in Arts and Science.	bea	ring in	mind t	hat there	e are wide	variatio	ns in cla	ıss size
		ext	remely ooor	very poor	poor	adequate	good	very good	outstanding
2.	Communicates goals and requirements of the course clearly								
	and explicitly		1	2	(3)	4	0	(6)	(7)
		B:	(1)	(2)	(3)	(4)	(5)	(6)	(7)
3.	Uses methods of evaluation (e.g. papers, assignments, tests) that appropriately reflect the subject matter and provide a fair evaluation								
	of student learning	A:	(1)	(2)	(3)	(4)		6	(7)
	•	B:	1	2	(3)	(4)	5	6	(7)
1	Presents material in an organized, well-planned manner	Δ.	<b>(1)</b>	2	(3)	(4)	(5)	0	(7)
٠.	riesents material in an organized, wen planned manner.	B:	1	(2)	(3)	(4)	(5)	6	7
5.	Explains concepts clearly with appropriate use of examples	A:	1	(2)	(3)	(4)		(6)	7
		B:	(1)	(2)	(3)	4	(5)	6	7
6	Communicates enthusiasm and interest in the course material	A:	(T)	(2)	(3)	(4)	<b>a</b> .	(6)	(7)
		В:	1	2	(3)	4	(5)	6	7
7.	Attends to students' questions and answers them clearly	۸.	1	(2)	(3)	(4)		(6)	(7)
	and effectively.		(I)	(2)	(3)	(4)	(5)	6	(7)
8.	Is available for individual consultation, by appointment or stated	٥.							
	office hours, to students with problems relating to the course	A:	1	(2)	(3)	4		6	(7)
		B:	1	(2)	(3)	4	(5)	(6)	(7)
9.	Ensures that student work is graded fairly, with helpful comments and feedback where appropriate.	A:	1	(2)	3	4		6	(7)
	und recubusit unere appropriates.		1	(2)	3	4)	(5)	6	(7)
10	Ensures that student work is graded within a reasonable time	Α:	(1)	(2)	3	4		6	7
10.	Enouge of the station work to graded within a seasonable tillor first		1	2	(3)	4	5	6	1

Statements about the course	: Respond to the s	tatements below,	using the	followi	ng 7-poi	nt scale.		9	SIDE 2
10.0			very low	low	below	average	above average	high	very high
12. Compared to other courses at th	ie same ievei (100,2	J0,300,400), the	0		0				
work load is	ne same level, the le	vel of difficulty of		(2)	3	4	5		7
the material is				(2)	(3)	4	5		(7)
14. The value of the required reading	g is		. 1	(2)	(3)	4		6	(7)
15. (If applicable) The value of the tu	utorials is		. 1	(2)	(3)		(5)	6	(7)
<ol><li>(If applicable) The value of the la</li></ol>	aboratories is		. 1	(2)	(3)		(5)	6	(7)
17. (If applicable) The value of the s	eminars is		. 1	2	(3)		(5)	(6)	(7)
18. (If applicable) The value of the la	anguage conversation	on classes is	. 1	(2)	(3)		5	6	7
<ol><li>The value of the overall learning</li></ol>	experience is		(1)	(2)	(3)		5	6	(7)
20. Considering your experience with meet program or degree require	th this course, and o ments, would you s	lisregarding your i	need for it course?	to	◯ Ye	S	No		
Statements about yourself:									
21. Number of full course credits al									
1) 0-41/2 2) 5-91/2 22. Status of the course for you:	3 10-14½	4 15-19 <sup>1</sup> /2		≥20					
	Colonted from a r	aguired list in a pro-	3 K G 100	/2 D.			770	0 " 1	
23. Your level of enthusiasm to take	2 Selected from a r	equired list in a prot	gram tration	3 Bre	eadth Requ	urement	(4)	Optional	
low (2) medium	3) high	ille of illitial regis	tration:						
24. Your expected grade in this cou									
1) <50 (2) 50-59	<u>3</u> 60-69	<b>7</b> 0-79	(5)	≥80					
Additional statements or que	estions which m	nav be supplied	d in clas	s:					
Additional statements or que					E E 7		24	0 0 0	(F. (E. )
<b>25.</b> (1) (2) (3) (4) (5) (6) (7)	28. 1 2 3 4	5 6 7	31. 🕦 (	2 (3) (4)	(5) (6) (7)			2 3 4	
25. (1 (2 (3) (4) (5) (6) (7) 26. (1 (2) (3) (4) (5) (6) (7)	28. 1 2 3 4 2 29. 1 2 3 4	5 (6) (7) 5 (6) (7)	31. <u>1</u> (	2 3 4 2 3 4	(5) (6) (7)		35. 🕕	2)(3)(4)	5 6 7
<b>25.</b> (1) (2) (3) (4) (5) (6) (7)	28. 1 2 3 4	5 (6) (7) 5 (6) (7)	31. <u>1</u> (	2 3 4 2 3 4			35. 🕕		5 6 7
25. 1 2 3 4 5 6 7 26. 1 2 3 4 5 6 7 27. 1 2 3 4 5 6 7	28. (1) (2) (3) (4) (29. (1) (2) (3) (4) (30. (1) (2) (3) (4) (4)	5 (6) (7) 5 (6) (7) 5 (6) (7)	31. (1) (32. (1) (33. (1) (	2 (3) (4) 2 (3) (4) 2 (3) (4)	(5) (6) (7) (5) (6) (7)		35. <u>1</u> 36. <u>1</u>	(2) (3) (4) (2) (3) (4)	(5) (6) (7) (5) (6) (7)
25. 1) 2 3 4 5 6 7 26. 1) 2 3 4 5 6 7 27. 1) 2 3 4 5 6 7	28. (1) (2) (3) (4) (2) (3) (4) (3) (4) (4) (4) (4) (4) (4) (4) (4) (4) (4	5 6 7 5 6 7 5 6 7	31. (1) (32. (1) (33. (1) (1) (1) (1) (1) (1) (1) (1) (1) (1)	2 3 4 2 3 4 2 3 4 2 the space	(5) (6) (7) (5) (6) (7) (ce below to	to provide	35. (1) 36. (1) e supplen	(2) (3) (4) (2) (3) (4) nentary c	(5) (6) (7) (5) (6) (7)
25. (1 (2 (3) (4) (5) (6) (7) 26. (1 (2) (3) (4) (5) (6) (7)	28. (1) (2) (3) (4) (2) (3) (4) (3) (4) (4) (4) (4) (4) (4) (4) (4) (4) (4	5 6 7 5 6 7 5 6 7	31. (1) (32. (1) (33. (1) (1) (1) (1) (1) (1) (1) (1) (1) (1)	2 3 4 2 3 4 2 3 4 2 the space	(5) (6) (7) (5) (6) (7) (ce below to	to provide	35. (1) 36. (1) e supplen	(2) (3) (4) (2) (3) (4) nentary c	(5) (6) (7) (5) (6) (7)





Note that survey results will be available to the instructor(s) only after final course marks have been submitted.

PART I: INSTRUCTIONS. PLEASE READ FIRST.							
Using an HB pencil or a blue or black ball-point pen (but not a for corresponding to your response for each statement. If using a pen,	elt marking do not alte	<b>g pen), f</b> er origina	<b>ill comp</b> l respon	<b>letely the</b> se by makin	<b>number</b> ng anoth	<b>ed oval</b> er select	ion.
Part II (on the reverse side) requires a written answer.							
Course Identification: Please print course and section you are evaluate	ing						
COURSE MATHOLIHIS SECTION 510  1. If evaluating only one instructor, write the name in the upper (A) box. two instructors, write their names, one in box A and the other in box E	If evaluating	g A:		INSTRU Dic	JCTOR	(S):	
DO NOT EVALUATE TEACHING ASSISTANTS ON THIS FO	ORM	2.					
Statements about the instructor(s):  Respond to the statements below for instructor A (and instructor B)	bearing in	ı mind tl	nat ther	e are wide	variatio	ns in cla	ass size
and subject matter in Arts and Science.							
	extremely poor	very poor	poor	adequate	good	very good	outstanding
2. Communicates goals and requirements of the course clearly	Δ. (1)		(3)	×	(5)	6	(7)
and explicitly.	. A: 1 B: 1	(2)	(3)	4)	(5)	6	7
3. Uses methods of evaluation (e.g. papers, assignments, tests) that							
appropriately reflect the subject matter and provide a fair evaluation			X		(5)	6	(7)
of student learning	B: 1	(2)	(3)	(4)	(5)	(6)	(7)
	<b>D</b>						
4. Presents material in an organized, well-planned manner	. A: ①	(2)	(3)	(4)	(5)	6	7
	B: 🕦	(2)	(3)	(4)	(5)	(6)	
5. Explains concepts clearly with appropriate use of examples	. A: ①	(2)	X	4	(5)	(6)	7
or Explains concepts steamy man appropriate	B: 1	2	(3)	4	(5)	6	7
a a company of the second seco	Λ. (1)	2	21	4	(5)	(6)	(7)
6. Communicates enthusiasm and interest in the course material	B: 1	(2)	(3)	4	(5)	6	(7)
7. Attends to students' questions and answers them clearly							
and effectively	. <u>A: 1</u>	(2)	(3)	X	5	(6)	(7)
a to the test of t	B: ①	(2)	(3)	(4)	5	6	
<ol><li>Is available for individual consultation, by appointment or stated office hours, to students with problems relating to the course</li></ol>	Δ: 1	(2)	(3)	×	(5)	6	(7)
office flours, to students with problems relating to the obtained from	B: ①	(2)	3	(4)	(5)	(6)	(7)
9. Ensures that student work is graded fairly, with helpful comments						C20	7001
and feedback where appropriate	. A: 1	(2)	(3)	<u> </u>	(5)	(6)	(7)
	B: (1)	(2)	(3)	4	(3)	(0)	
10. Ensures that student work is graded within a reasonable time	. A: 1	(2)	3	W1	(5)	(6)	(7)
William Towns and the Control of the	B: 1	2	(3)	4	(5)	6	(7)
11. All things considered, performs effectively as a university teacher	A		(0)	· · ·		10	
TAMONDA ASSESSED TO THE TAME ASSESSED ASSESSEDA ASSESSED ASSESSED ASSESSED ASSESSED ASSESSED ASSESSED ASSESSEDA							
11. All things considered, performs effectively as a difficulty teacher.	B: 1	(2)	(3)	(4)	(5)	(6)	(7)

Compared to other courses at the same level (100,200,300,400), the work load is  Compared to other courses at the same level, the level of difficulty of the material is  The value of the required reading is (If applicable) The value of the laboratories is (If applicable) The value of the laboratories is (If applicable) The value of the language conversation classes is The value of the overall learning experience is  Considering your experience with this course, and disregarding your meet program or degree requirements, would you still have taken this course tements about yourself:  Number of full course credits already earned (prior to this session):  (1) 0-4½ (2) 5-9½ (3) 10-14½ (4) 15-19½ (5) Status of the course for you: (5) Selected from a required list in a proor	eed for it course?	2 2 2 2 2 2 2 2 to	below average  3  3  3  3  3  Yes	average  (4) (4) (4) (4) (4) (4) (4) (4) (4) (5) (6) (7) (8) (8)	above average 5 5 5 5 5 5 5 5 5 5 5 6 6 6 6 6 6 6 6	high  X  X  X  X  X  X  X	very high
work load is  Compared to other courses at the same level, the level of difficulty of the material is  The value of the required reading is (If applicable) The value of the laboratories is (If applicable) The value of the laboratories is (If applicable) The value of the lamguage conversation classes is (If applicable) The value of the language conversation classes is The value of the overall learning experience is  Considering your experience with this course, and disregarding your meet program or degree requirements, would you still have taken this course.  tements about yourself:  Number of full course credits already earned (prior to this session):  1) 0-4½  2) 5-9½  Status of the course for you:  2) Selected from a required list in a program requirement	1 1 1 1 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0	(2) (2) (2) (2) (2) (2)	3 3 3 3 3 3 3	(4) (4) (4) (4) (4)	(5) (5) (5) (5) (5) (5)	X	7
Compared to other courses at the same level, the level of difficulty of the material is  The value of the required reading is (If applicable) The value of the tutorials is (If applicable) The value of the laboratories is (If applicable) The value of the laboratories is (If applicable) The value of the language conversation classes is The value of the overall learning experience is  Considering your experience with this course, and disregarding your meet program or degree requirements, would you still have taken this course tements about yourself:  Number of full course credits already earned (prior to this session):  (1) 0-4½ (2) 5-9½ (3) 10-14½ (4) 15-19½ (5) Status of the course for you: (5) Selected from a required list in a proor	1 1 1 1 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0	(2) (2) (2) (2) (2) (2)	3 3 3 3 3 3	(4) (4) (4) (4) (4)	(5) (5) (5) (5) (5)	X	7
The value of the required reading is  (If applicable) The value of the tutorials is  (If applicable) The value of the laboratories is  (If applicable) The value of the seminars is  (If applicable) The value of the seminars is  (If applicable) The value of the language conversation classes is  The value of the overall learning experience is  Considering your experience with this course, and disregarding your nemeet program or degree requirements, would you still have taken this course about yourself:  Number of full course credits already earned (prior to this session):  (1) 0-4½  2) 5-9½  3) 10-14½  4) 15-19½  Status of the course for you:  (2) Selected from a required list in a program requirement	1 1 1 1 eed for it	(2) (2) (2) (2) (2) (2)	3 3 3 3 3	(4) (4) (4) (4) (4)	(5) (5) (5) (5)		7
(If applicable) The value of the tutorials is	eed for it	2 (2) (2) (2)	3 3 3 3	(4) (4) (4) (4)	(5) (5) (5)		(7)
(If applicable) The value of the laboratories is	eed for it	(2) (2) (2)	3 3 3	4	(5) (5)		
(If applicable) The value of the seminars is (If applicable) The value of the language conversation classes is The value of the overall learning experience is Considering your experience with this course, and disregarding your nemeet program or degree requirements, would you still have taken this contemporary to the course of the course credits already earned (prior to this session):  (1) 0-4½ (2) 5-9½ (3) 10-14½ (4) 15-19½ (5) Status of the course for you: (5) Selected from a required list in a program Requirement	eed for it	2 2	(3) (3) (3)	4	(5) (5)		
(If applicable) The value of the language conversation classes is The value of the overall learning experience is	eed for it	2	3	4	(5)		(7)
The value of the overall learning experience is	eed for it course?					*	7
tements about yourself:  Number of full course credits already earned (prior to this session):  1 0-4½ 2 5-9½ 3 10-14½ 4 15-19½ Status of the course for you:  1 Program Requirement 2 Selected from a required list in a program.	course?	to	◯ Yes	S		-62	(7)
tements about yourself:  Number of full course credits already earned (prior to this session):  (1) 0-4½ (2) 5-9½ (3) 10-14½ (4) 15-19½ Status of the course for you:  (1) Program Requirement (2) Selected from a required list in a program			O Yes	S			
Number of full course credits already earned (prior to this session):  1 0-4½ 2 5-9½ 3 10-14½ 4 15-19½ Status of the course for you:  1 Program Requirement 2 Selected from a required list in a program.	(5)				O No		
Your level of enthusiasm to take this course at the time of initial registr  1 low 2 medium 3 high  Your expected grade in this course: 1 <50 2 50-59 3 60-69 4 70-79	am		readth Requ	uirement	4	Optional	
litional statements or questions which may be supplied  1 2 3 4 5 6 7 28. 1 2 3 4 5 6 7  1 2 3 4 5 6 7 29. 1 2 3 4 5 6 7  1 2 3 4 5 6 7 30. 1 2 3 4 5 6 7	31. ① ① 32. ① ②	2) (3) (4) 2) (3) (4)	5 6 7 5 6 7 5 6 7		34. ① (35. ① (36. ① (36. ① (36. ② (36. ② (36. ③ (36. ③ (36. ③ (36. ③ (36. ③ (36. ③ (36. ③ (36. ③ (36. ④ (36. ⑥ (36		(5) (6) (7) (5) (6) (7) (7) (8) (7)
II: PLEASE ANSWER ONLY AFTER COMPLETING PART I. Phe instructor(s) or course. For example, you may wish to give the reastestions for improving the instruction in the course.	Please use sons for y	the spa	ce below t merical ev	to providaluations	e supplem or provid	entary co	ommen





**INSTRUCTOR(S):** 

Note that survey results will be available to the instructor(s) only after final course marks have been submitted.

### PART I: INSTRUCTIONS. PLEASE READ FIRST.

Using an HB pencil or a blue or black ball-point pen (but not a felt marking pen), fill completely the numbered oval corresponding to your response for each statement. If using a pen, do not alter original response by making another selection.

**SECTION** 

Part II (on the reverse side) requires a written answer.

7. Attends to students' questions and answers them clearly

8. Is available for individual consultation, by appointment or stated

9. Ensures that student work is graded fairly, with helpful comments

10. Ensures that student work is graded within a reasonable time. . . . .

11. All things considered, performs effectively as a university teacher. . . A: 1

office hours, to students with problems relating to the course. . .

and effectively. . . . .

**COURSE** 

Course Identification: Please print course and section you are evaluating

If evaluating only one instructor, write the name in the upper (A) box.     two instructors, write their names, one in box A and the other in box B.	lf evaluatin 3.	$g \qquad \frac{A}{B}$		N Ba	ur Na	ten	
DO NOT EVALUATE TEACHING ASSISTANTS ON THIS FO		В	•				
Statements about the instructor(s):							
Respond to the statements below for instructor A (and instructor B) and subject matter in Arts and Science.	bearing in	n mind t	hat ther	e are wide	variatio	ns in cla	ass size
	extremely poor	very poor	poor	adequate	good	very	outstanding
Communicates goals and requirements of the course clearly and explicitly.	•	(2)	(3)	4	•	6	7
	B: 1	(2)	(3)	4	(5)	6	7
<ol><li>Uses methods of evaluation (e.g. papers, assignments, tests) that appropriately reflect the subject matter and provide a fair evaluation</li></ol>							
of student learning	. A: 1	2	(3)	•	(5)	6	(7)
	B: 1	2	3	4	5	6	
4. Presents material in an organized, well-planned manner	. A: ①	(2)	(3)		(5)	(6)	(7)
4. I reserve material in an organized, were planned material in the server of the serv	B: 1	(2)	(3)	4	(5)	(6)	(7)
5. Explains concepts clearly with appropriate use of examples	. A: ①	(2)	(3)	(5)	(5)	6	(7)
o. Explains concepts disarry with appropriate ass of oxampion 11111	B: 1	(2)	(3)	4	(5)	6	7
6. Communicates anthusiasm and interest in the course material	Λ. ①	(2)	(3)	(4)		(6)	(7)

. A: 1

A: 1

A: 1 B: 1

A: 1

2

2

### PART I CONTINUES ON THE REVERSE SIDE

6

6

9

(7)

(7)

Statements about the course: Respond to the	he statements below,	using the	e follow	ing 7-poi	nt scale.		9	SIDE
2. Communal to other courses at the course level (46	20.000.000.400\	very low	low	below average	average	above average	high	very high
Compared to other courses at the same level (10 work load is	JU,200,300,400), the	. a	(2)	(3)	4	5	6	angii
3. Compared to other courses at the same level, th	e level of difficulty of		(4)	0	4	3	0	
the material is		. 1	(2)	3	4	(5)	6	1
4. The value of the required reading is		. 1	(2)	1	4	(5)	(6)	(7)
5. (If applicable) The value of the tutorials is			2	(3)	4	(5)	6	7
6. (If applicable) The value of the laboratories is		. 1	(2)	(3)	4	(5)	6	7
7. (If applicable) The value of the seminars is	.,,,,	. 1	(2)	(3)	(4)	(5)	(6)	7
3. (If applicable) The value of the language convers	sation classes is	(D)	(2)	(3)	(4)	5	6	7
D. The value of the overall learning experience is .		(1)	2	(3)	(4)	5	6	7
. Considering your experience with this course, a	nd disregarding your	need for it	to					
meet program or degree requirements, would yo	ou still have taken this	course?		O Ye	S	No	)	
1. 0-4½ 2 5-9½ 3 10-14½ 2. Status of the course for you:  Program Requirement 2 Selected from	n a required list in a prod	gram	≥20 ③ B	readth Req	uirement	4	Optional	
2. Status of the course for you:	n a required list in a prod	gram		readth Req	uirement	4	Optional	
1. 0-4½ 2 5-9½ 3 10-14½ 2. Status of the course for you: 3 Program Requirement 2 Selected from Your level of enthusiasm to take this course at to low 2 medium 3 high	n a required list in a prod	gram tration:		readth Req	uirement	4	Optional	
1. 0-4½ (2) 5-9½ (3) 10-14½ 2. Status of the course for you: 3. Program Requirement (2) Selected from (3) low (2) medium (3) high (4) 450 (2) 50-59 (3) 60-69	15-19½  a required list in a proghe time of initial regist	gram tration:	3 B ≥80	readth Req	uirement	4	Optional	
1. 0-4½ 2 5-9½ 3 10-14½ 2. Status of the course for you: 3. Program Requirement 2 Selected from 5. Your level of enthusiasm to take this course at t 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	15-19½  n a required list in a progene time of initial regist  10-79  n may be supplied	gram tration: (5)	3 Bi ≥80	readth Req	uirement		Optional	(5) (6) (7)
2. Status of the course for you:  Program Requirement 2. Selected from 2. Selected from 3. Your level of enthusiasm to take this course at the selected grade in this course:  1. <50 2. 50-59 3. 60-69  dditional statements or questions which	15-19½  n a required list in a prophe time of initial regist  4 70-79  n may be supplied	gram tration: 5 d in clas 31. (1)	3 Bi ≥80	5 6 7	uirement		<ul><li>(2) (3) (4)</li></ul>	(5) (6) (7 (5) (6) (7



Note that survey results will be available to the instructor(s) only after final course marks have been submitted.

Using an HB pencil or a blue or black ball-point pen (but not a felt marking pen), fill completely the numbered oval

PART I: INSTRUCTIONS. PLEASE READ FIRST.

### corresponding to your response for each statement. If using a pen, do not alter original response by making another selection. Part II (on the reverse side) requires a written answer. Course Identification: Please print course and section you are evaluating **COURSE** HI SECTION **INSTRUCTOR(S):** A: Dror Bar Natan 1. If evaluating only one instructor, write the name in the upper (A) box. If evaluating two instructors, write their names, one in box A and the other in box B. B: DO NOT EVALUATE TEACHING ASSISTANTS ON THIS FORM Statements about the instructor(s): Respond to the statements below for instructor A (and instructor B) bearing in mind that there are wide variations in class size and subject matter in Arts and Science. outstanding extremely adequate 2. Communicates goals and requirements of the course clearly 3. Uses methods of evaluation (e.g. papers, assignments, tests) that appropriately reflect the subject matter and provide a fair evaluation 6. Communicates enthusiasm and interest in the course material. . . . . A: 1 7. Attends to students' questions and answers them clearly and effectively. . . . . . 8. Is available for individual consultation, by appointment or stated A: 1 office hours, to students with problems relating to the course. . . . . . 6 9. Ensures that student work is graded fairly, with helpful comments A: 1 B: 1 10. Ensures that student work is graded within a reasonable time. . . . . A: 1 6 11. All things considered, performs effectively as a university teacher. ... A: (1

State	ements about the cours	e: Respond	to the star	tements below,	using the	followi	ng 7-poi	nt scale.		S	SIDE 2
					very low	low	below	average	above average	high	very high
	Compared to other courses at										
12 C	vork load is	bo come lov	al the level	of difficulty of	1	(2)	3		(5)	6	7
	he material is				<b>(1</b> )	2	(3)	(4)	(5)		(7)
14 T	he value of the required readi	na ie			. D	(2)	(3)	4	(5)	(6)	7
15 (1	If applicable) The value of the	tutoriale ie			. 1	(2)	(3)	4	(5)	6	7
	If applicable) The value of the					(2)	(3)	4	(5)	6	7
7. (1	If applicable) The value of the	seminare is	10		. 0	(2)	(3)	4	(5)	(6)	7
	If applicable) The value of the					(2)	(3)	4	(5)	6	7
	he value of the overall learnin					(2)	(3)	4		6	7
	Considering your experience w							(4)		0	
2U. C			oo, alle ale		IIIOOG IOI IL						
n State	neet program or degree requirements about yourself:	· ·	•	have taken this	course?		◯ Ye	S	No		
otate 21. N		already earne (3) 1 (2) Selected	ed (prior to 0-14½ d from a regi	this session):  15-19½  uired list in a pro	(5) j		◯ Ye			Optional	
otate 21. N 22. S 23. Y	ements about yourself: Number of full course credits a 10 0-41/2 2 5-91/2 10	already earne 3 1 2 Selected 4 this cours 3 h	ed (prior to 0-14½ d from a requ e at the tim	this session):  15-19½  uired list in a pro	(5) j					Optional	
otate 21. N 22. S 23. Y	ements about yourself: Number of full course credits a 10 0-41/2 2 5-91/2 Status of the course for you: Program Requirement Your level of enthusiasm to tak 11 low medium Your expected grade in this co	already earne 3 1 2 Selected 4 this cours 3 h 4 urse:	ed (prior to 0-14½ d from a reques at the times igh	this session):  15-19½  uired list in a pro	(5) j					Optional	
otate 21. N 22. S 23. Y	ements about yourself: Number of full course credits a 10 0-41/2 2 5-91/2 10	already earne 3 1 2 Selected 4 this cours 3 h	ed (prior to 0-14½ d from a reques at the times igh	this session):  15-19½  uired list in a pro	(5) j	③ Br				Optional	



### FACULTY OF ARTS & SCIENCE

INSTRUCTOR(S):

A: [

B:

Note that survey results will be available to the instructor(s) only after final course marks have been submitted.

### PART I: INSTRUCTIONS. PLEASE READ FIRST.

Using an HB pencil or a blue or black ball-point pen (but not a felt marking pen), fill completely the numbered oval corresponding to your response for each statement. If using a pen, do not alter original response by making another selection.

**SECTION** 

Part II (on the reverse side) requires a written answer.

**COURSE** 

Course Identification: Please print course and section you are evaluating

1. If evaluating only one instructor, write the name in the upper (A) box. If evaluating two instructors, write their names, one in box A and the other in box B.

DO NOT EVALUATE TEACHING ASSISTANTS ON THIS FORM

Sta	itements about the instructor(s):							
	spond to the statements below for instructor A (and instructor B) I subject matter in Arts and Science.	bearing ir	n mind t	hat ther	e are wide	variatio	ns in cla	ass size
		extremely poor	very	poor	adequate	good	very	outstanding
2.	Communicates goals and requirements of the course clearly						0	
	and explicitly		(2)	3	4	5		(7)
		B: 1	2	3	4	(5)	6	7
3.	Uses methods of evaluation (e.g. papers, assignments, tests) that appropriately reflect the subject matter and provide a fair evaluation							
	of student learning		(2)	(3)	4	(5)	(5)	7
		B: 1	2	(3)	4	5	6	(7)
4.	Presents material in an organized, well-planned manner	A: 1	2	(3)	4	(5)		(7)
	,	B: 1	(2)	(3)	(4)	(5)	(6)	(7)
5.	Explains concepts clearly with appropriate use of examples	A: 1	(2)	3	4	5		7
	, , , , , , , , , , , , , , , , , , , ,	B: 1	(2)	(3)	4	(5)	6	(7)
6.	Communicates enthusiasm and interest in the course material	A: ①	(2)	3	4	(5)	-	(7)
		B: 1	(2)	(3)	4	(5)	6	(7)
7.	Attends to students' questions and answers them clearly					- mile		
	and effectively		2	(3)	4	<b>B</b>	(6)	7
		B: 1	2	(3)	4	(5)	6	(7)
8.	Is available for individual consultation, by appointment or stated					-		
	office hours, to students with problems relating to the course		2	(3)	4		6	7
		B: ①	2	(3)	4	(5)	6	(7)
9.	Ensures that student work is graded fairly, with helpful comments	A - (4)	(0)			(5)		(=)
	and feedback where appropriate	A: 1 B: 1	2	(3)	4	(5)	6	(7)
		D: 🕕	(2)	(3)	(4)	3	(6)	
10.	Ensures that student work is graded within a reasonable time	A: 1	(2)	(3)	4	(5)	(S)	(7)
		B: 1	(2)	(3)	4	(5)	6	(7)
11.	All things considered, performs effectively as a university teacher	A: ①	2	(3)	4	(5)		(7)
		B: 1	(2)	(3)	(4)	(5)	(6)	(7).

Statements about the course: Respond to the statements below,	using the	followi	ng 7-poir	t scale.			SIDE 2
	very low	low	below	average	above	high	very high
12. Compared to other courses at the same level (100,200,300,400), the			average		average		high
work load is	1	(2)	(3)	4	6	6	7
13. Compared to other courses at the same level, the level of difficulty of							
the material is	1	(2)	(3)	(4)		6	7
14. The value of the required reading is	1	(2)	3	(4)	<b>(</b>	6	(7)
15. (If applicable) The value of the tutorials is	(1)	(2)	3	4	(5)	6	(7)
16. (If applicable) The value of the laboratories is	1	(2)	(3)	(4)	(5)	6	7
17. (If applicable) The value of the seminars is	1	2	3	(4)	(5)	6	7
18. (If applicable) The value of the language conversation classes is	(D)	(2)	3	4	(5)	6	(7)
The value of the overall learning experience is		(2)	3	(4)	0	6	(7)
meet program or degree requirements, would you still have taken this constant should yourself:			Yes	3	O No		
21. Number of full course credits already earned (prior to this session):							
1 $0-4\frac{1}{2}$ 2 $5-9\frac{1}{2}$ $10-14\frac{1}{2}$ 4 $15-19\frac{1}{2}$	(5) 2	> 20					
22. Status of the course for you:		_20					
<ul><li>Program Requirement</li><li>Selected from a required list in a program</li></ul>	ram	(3) Br	eadth Regu	irement	(4)	Optiona	d
23. Your level of enthusiasm to take this course at the time of initial registr	ation:	U DI	cadin nequ	mornorit		Optione	u
1 low medium 3 high	u						
24. Your expected grade in this course:							
(1 <50 (2 50-59 (3 60-69 (4 70-79	<b>(</b>	≥80					
Additional statements or questions which may be supplied	in clas	s:					
25. 1 2 3 4 5 6 7 28. 1 2 3 4 5 6 7			(5) (6) (7)		34.	2)(3)(	4 (5) (6) (7)
26. 1 2 3 4 5 6 7 29. 1 2 3 4 5 6 7	32.	2 (3) (4)	(5) (6) (7)		35.	2 3	4 (5) (6) (7)
27. 1 2 3 4 5 6 7 30. 1 2 3 4 5 6 7			(5) (6) (7)				4 (5) (6) (7)

PART II: PLEASE ANSWER ONLY AFTER COMPLETING PART I. Please use the space below to provide supplementary comments on the instructor(s) or course. For example, you may wish to give the reasons for your numerical evaluations or provide specific suggestions for improving the instruction in the course.





Note that survey results will be available to the instructor(s) only after final course marks have been submitted.

### PART I: INSTRUCTIONS. PLEASE READ FIRST.

Using an HB pencil or a blue or black ball-point pen (but not a felt marking pen), fill completely the numbered oval corresponding to your response for each statement. If using a pen, do not alter original response by making another selection.

Part II (on the reverse side) requires a written answer.

Course Identification: Please print course and section you are evaluating

11. All things considered, performs effectively as a university teacher. .. A: 1

	COURSE   M A T 4 0	011			INSTRU	CTOR(S	S):	
1.	If evaluating only one instructor, write the name in the upper (A) box. If two instructors, write their names, one in box A and the other in box B.		A: B:	DROR	BAR	NA	NAJ	
	DO NOT EVALUATE TEACHING ASSISTANTS ON THIS FOR	RM						
ita	tements about the instructor(s):							
	spond to the statements below for instructor A (and instructor B) leads to the statements and Science.							
nc	subject matter in Arts and Science.	extremely	very	poor	are wide v	good	very good	ss size
nc	Subject matter in Arts and Science.  Communicates goals and requirements of the course clearly and explicitly.	extremely poor  A: 1	very					
2.	Communicates goals and requirements of the course clearly and explicitly.  Uses methods of evaluation (e.g. papers, assignments, tests) that appropriately reflect the subject matter and provide a fair evaluation	extremely poor  A: 1 B: 1	very poor 2	poor 3 3	adequate	good 5	very good 6	outstandin
2.	Subject matter in Arts and Science.  Communicates goals and requirements of the course clearly and explicitly.  Uses methods of evaluation (e.g. papers, assignments, tests) that appropriately reflect the subject matter and provide a fair evaluation	extremely poor  A: 1	very poor	poor	adequate	good 5	very good	outstandin

### 5. Explains concepts clearly with appropriate use of examples. . . . . . . A: 11 6. Communicates enthusiasm and interest in the course material. . . . . . A: 1 7. Attends to students' questions and answers them clearly .....<u>A: 1</u> and effectively. . . . . . 8. Is available for individual consultation, by appointment or stated A: 1 office hours, to students with problems relating to the course. . . . . . . 9. Ensures that student work is graded fairly, with helpful comments 10. Ensures that student work is graded within a reasonable time. . . . . .

tatements about the course: Respond to the statements below,	using the	followi	ng 7-poi	nt scale.		S	SIDE
	very low	low	below average	average	above average	high	very high
2. Compared to other courses at the same level (100,200,300,400), the work load is	Ť	2	(3)	4)	average		
. Compared to other courses at the same level, the level of difficulty of		(2)	(3)	(4)		6	7
the material is	(1)	(2)	(3)	4	(5)		(7)
. The value of the required reading is	1	(2)	(3)	4	(5)	0	(7)
. (If applicable) The value of the tutorials is	1	(2)	(3)	(4)	5	(6)	(7)
(If applicable) The value of the laboratories is	1	(2)	(3)	4	(5)	(6)	(7)
(If applicable) The value of the seminars is	1	(2)	3	4	5	6	(7)
(If applicable) The value of the language conversation classes is	1	(2)	3	4	5	6	7
The value of the overall learning experience is	ood for it	2	3	4	(5)		(7)
meet program or degree requirements, would you still have taken this	eed for it	10	C Ye	•	No		
Number of full course credits already earned (prior to this session):  1 0-41/2 2 5-91/2 10-141/2 15-191/2 Status of the course for you:  Program Requirement 2 Selected from a required list in a program	(5) ; ram ration:		eadth Requ	uirement	4	Optional	
Number of full course credits already earned (prior to this session):  1 0-41/2 2 5-91/2 10-141/2 15-191/2 Status of the course for you: Program Requirement 2 Selected from a required list in a program level of enthusiasm to take this course at the time of initial registress of the course of the course at the time of initial registress of the course at the time of initial registress of the course at the time of initial registress of the course at the time of initial registress of the course of the course at the time of initial registress of the course of t	ram	3 Bro	eadth Requ	uirement	(4)	Optional	
2. Status of the course for you:  Program Requirement  Selected from a required list in a program level of enthusiasm to take this course at the time of initial registred low  medium  high  Your expected grade in this course:	ram ration:  5 2  l in clas 31. 11	3 Bro	(5) (6) (7)	uirement	34. ① 35. ①	Optional  2 (3 (4) 2 (3 (4) 2 (3 (4)	(5) (6) ( (5) (6) ( (5) (6) (





Note that survey results will be available to the instructor(s) only after final course marks have been submitted.

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(a) (7) (b) (7)
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(6) (7) (6) (7) (6) (7)

Compared to other courses at the same level (100,200,300,400), the work load is  Compared to other courses at the same level, the level of difficulty of the material is  The value of the required reading is (If applicable) The value of the tutorials is (If applicable) The value of the laboratories is (If applicable) The value of the seminars is (If applicable) The value of the language conversation classes is The value of the overall learning experience is Considering your experience with this course, and disregarding your meet program or degree requirements, would you still have taken this  tements about yourself:  Number of full course credits already earned (prior to this session):  1 0-41/2 2 5-91/2 3 10-141/2	. (1) . (1) . (1) . (1) . (1) . (1) . (1)	2 (2) (2) (2) (2) (2) (2) (2) (2) (2) (2	below average	average	above average	high	very high
work load is  Compared to other courses at the same level, the level of difficulty of the material is  The value of the required reading is (If applicable) The value of the tutorials is (If applicable) The value of the laboratories is (If applicable) The value of the seminars is (If applicable) The value of the language conversation classes is The value of the overall learning experience is Considering your experience with this course, and disregarding your meet program or degree requirements, would you still have taken this  tements about yourself: Number of full course credits already earned (prior to this session):	. (1) . (1) . (1) . (1) . (1) . (1) . (1)	(2) (2) (2) (2) (2)	3 3 3 3 3	4	( <b>5</b> )		
Compared to other courses at the same level, the level of difficulty of the material is  The value of the required reading is (If applicable) The value of the tutorials is (If applicable) The value of the laboratories is (If applicable) The value of the seminars is (If applicable) The value of the language conversation classes is (If applicable) The value of the language conversation classes is  Considering your experience with this course, and disregarding your meet program or degree requirements, would you still have taken this  tements about yourself:  Number of full course credits already earned (prior to this session):	. (1) . (1) . (1) . (1) . (1) . (1) . (1)	(2) (2) (2) (2)	(3) (3)	4			
The value of the required reading is (If applicable) The value of the tutorials is (If applicable) The value of the laboratories is (If applicable) The value of the seminars is (If applicable) The value of the language conversation classes is The value of the overall learning experience is Considering your experience with this course, and disregarding your meet program or degree requirements, would you still have taken this  tements about yourself: Number of full course credits already earned (prior to this session):	. (1) . (1) . (1) . (1) . (1) . (1) need for it	(2) (2) (2) (2)	(3) (3)	4			
(If applicable) The value of the tutorials is	. (1) . (1) . (1) . (1) . (1) need for it	(2) (2)	(3)			6	7
(If applicable) The value of the seminars is	. ① . ① ① need for it	(2) (2)			(5)	6	(7)
(If applicable) The value of the language conversation classes is The value of the overall learning experience is Considering your experience with this course, and disregarding your meet program or degree requirements, would you still have taken this tements about yourself: Number of full course credits already earned (prior to this session):			(3)	4	5	6	7
Considering your experience with this course, and disregarding your meet program or degree requirements, would you still have taken this tements about yourself:  Number of full course credits already earned (prior to this session):	need for it		3	(4)	5	6	(7)
meet program or degree requirements, would you still have taken this tements about yourself:  Number of full course credits already earned (prior to this session):		t to	(3)	4		(6)	7
Number of full course credits already earned (prior to this session):			Ye	S	No	)	
Number of full course credits already earned (prior to this session):							
	(5)	≥20					
Status of the course for you:  Program Requirement  Selected from a required list in a pro-	aram	(3) Br	eadth Reg	iirement	(A)	Optional	
Your level of enthusiasm to take this course at the time of initial regis	tration:	<u> </u>	caatiiiicq	ancment	•	Optional	
1) low							
① <50 ② 50-59 <b>②</b> 60-69 ④ 70-79	(5)	≥80					
I II: PLEASE ANSWER ONLY AFTER COMPLETING PART I. the instructor(s) or course. For example, you may wish to give the re	Please us	e the spa	ce below merical ev	to provid aluations	e supplen	nentary c	ommei
gestions for improving the instruction in the course.		your ma	incircui ev	anations	or provid	ac specifi	C
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### FACULTY OF ARTS & SCIENCE

INSTRUCTOR(S):

A: D. BAR NATAN

B:

Note that survey results will be available to the instructor(s) only after final course marks have been submitted.

### PART I: INSTRUCTIONS. PLEASE READ FIRST.

Using an HB pencil or a blue or black ball-point pen (but not a felt marking pen), fill completely the numbered oval corresponding to your response for each statement. If using a pen, do not alter original response by making another selection.

**SECTION** 

Part II (on the reverse side) requires a written answer.

**COURSE** 

Course Identification: Please print course and section you are evaluating

10. Ensures that student work is graded within a reasonable time. . . . . . .

11. All things considered, performs effectively as a university teacher. . . A: 1

 If evaluating only one instructor, write the name in the upper (A) box. If evaluating two instructors, write their names, one in box A and the other in box B.

	DO NOT EVALUATE TEACHING ASSISTANTS ON THIS FO	ORM						
Sta	tements about the instructor(s):							
	pond to the statements below for instructor A (and instructor B) I subject matter in Arts and Science.	bearing i	n mind t	hat ther	e are wide	variatio	ns in cla	ass size
		extremely	very	poor	adequate	good	very	outstanding
2.	Communicates goals and requirements of the course clearly		Poor				Base	
	and explicitly	. A: ①	(2)	(3)	(4)	-	(6)	7)
		B: 1	(2)	(3)	4	(5)	(6)	(7)
3.	Uses methods of evaluation (e.g. papers, assignments, tests) that appropriately reflect the subject matter and provide a fair evaluation							
	of student learning	. A: 🕦	(2)		4	(5)	(6)	(7)
		B: ①	(2)	(3)	4	(5)	6	(7)
4.	Presents material in an organized, well-planned manner		(2)	(3)	0	(5)	(6)	(7)
		B: 1	2	3	4	(5)	(6)	(7)
5.	Explains concepts clearly with appropriate use of examples	. A: 🕦	(2)	(3)	4	(5)	-	(7)
		B: ①	(2)	(3)	4	(5)	(6)	(7)
6.	Communicates enthusiasm and interest in the course material		(2)	(3)	4	(5)		(7)
		B: 🕦	(2)	(3)	4	(5)	6	(7)
7.	Attends to students' questions and answers them clearly							
	and effectively	. A: 🕕	(2)	(3)	(4)	(5)	4	(7)
Ω	Is available for individual consultation, by appointment or stated	B: ①	2	(3)	4	(5)	(6)	(7)
0.	office hours, to students with problems relating to the course	Δ. 1	(2)	(3)	(4)		6	(7)
		B: 1	2	3	4)	(5)	(6)	7
9.	Ensures that student work is graded fairly, with helpful comments		750	2020		2000		7
	and feedback where appropriate	. A: 1	2	(3)	<b>(2)</b>	5	(6)	(7)

Statements about the course: Respond to the statements below, using the following 7-point scale.  12. Compared to other courses at the same level (100,200,300,400), the work load is.  13. Compared to other courses at the same level, the level of difficulty of the value of the required reading is.  14. The value of the required reading is.  15. (if applicable) The value of the laboratories is.  16. (if applicable) The value of the sentinars is.  17. (if applicable) The value of the sentinars is.  18. (if applicable) The value of the sentinars is.  19. (if applicable) The value of the								
12. Compared to other courses at the same level (100,200,300,400), the work load is	Statements about the course: Respond to the statements below	w, using t	he follow	ing 7-poi	nt scale.			SIDE 2
3. Compared to other courses at the same level, the level of difficulty of the material is				below				very
13. Compared to other courses at the same level, the level of difficulty of the materials		(1)	(2)				(6)	
14. The value of the required reading is	13. Compared to other courses at the same level, the level of difficulty of	of					0	
16. (If applicable) The value of the laboratories is								
17. (if applicable) The value of the seminars is	15. (If applicable) The value of the tutorials is	1		3		(5)		(7)
19. The value of the overall learning experience is								
20. Considering your experience with this course, and disregarding your need for it to meet program or degree requirements, would you still have taken this course?  **No**  **Statements about yourself:**  21. Number of full course credits already earned (prior to this session):  1 0-4½ 25-9½ 310-14½ 15-19½ 5≥20  22. Status of the course for you:  2 Program Requirement 2 Selected from a required list in a program 3 Breadth Requirement 4 Optional 23. Your level of enthusiasm to take this course at the time of initial registration:  1 1 100 2 2 medium 1 high 1 high 2 medium 1 high 1 high 2 medium 2 hi								
Statements about yourself:  21. Number of full course credits already earned (prior to this session):  1 0.4½ 2 5.9½ 3 10.14½ 15.19½ 5 ≥20  22. Status of the course for you:  Program Requirement 2 Selected from a required list in a program 23. Your level of enthusiasm to take this course at the time of initial registration:  1   10 w   2   2   medium	20. Considering your experience with this course, and disregarding you	ır need for	it to					
21. Number of full course credits already earned (prior to this session):    0.4½   2.5.9½   3   10.14½   6   15.19½   5   20   Program Requirement   2. Selected from a required list in a program   3. Breadth Requirement   4. Optional	meet program or degree requirements, would you still have taken th	is course?		✓ Ye	S	O No	).	
24. Your expected grade in this course:  1 <50  25.59  60.69  1 70.79  5 ≥ 80   Additional statements or questions which may be supplied in class:  25. 1 2 3 4 5 6 7  28. 1 2 3 4 5 6 7  30. 1 2 3 4 5 6 7  31. 1 2 3 4 5 6 7  35. 1 2 3 4 5 6 7  36. 1 2 3 4 5 6 7  37. 1 2 3 4 5 6 7  38. 1 2 3 4 5 6 7  39. 1 2 3 4 5 6 7  30. 1 2 3 4 5 6 7  31. 1 2 3 4 5 6 7  36. 1 2 3 4 5 6 7  37. 1 2 3 4 5 6 7  38. 1 2 3 4 5 6 7  39. 1 2 3 4 5 6 7  30. 1 2 3 4 5 6 7	<ul> <li>21. Number of full course credits already earned (prior to this session):</li> <li>1 0-4½</li> <li>2 5-9½</li> <li>3 10-14½</li> <li>15-19½</li> <li>22. Status of the course for you:</li> <li>Program Requirement</li> <li>2 Selected from a required list in a prior of this session):</li> <li>3 10-14½</li> <li>4 15-19½</li> <li>2 Selected from a required list in a prior of this session):</li> </ul>	rogram		readth Req	uirement	<b>(4)</b>	Optional	
Additional statements or questions which may be supplied in class:  25. 12 3 4 5 6 7 28. 1 2 3 4 5 6 7 31. 12 3 4 5 6 7 34. 1 2 3 4 5 6 7  26. 12 3 4 5 6 7 29. 12 3 4 5 6 7 32. 12 3 4 5 6 7 35. 12 3 4 5 6 7  27. 12 3 4 5 6 7 30. 12 3 4 5 6 7 33. 12 3 4 5 6 7 36. 12 3 4 5 6 7  2ART II: PLEASE ANSWER ONLY AFTER COMPLETING PART I. Please use the space below to provide supplementary comment on the instructor(s) or course. For example, you may wish to give the reasons for your numerical evaluations or provide specific suggestions for improving the instruction in the course.  - TA does not mark assignments fairly  Professor loses his train of thought quite of ten  - He is vary enthusiastic about the naterial in class  - Exams are extremely difficult compared to the neltly  assignments	1 low 2 medium 🔊 high	istration:						
25. 12 3 4 5 6 7 28. 12 3 4 5 6 7 31. 12 3 4 5 6 7 34. 12 3 4 5 6 7 35. 12 3 4 5 6 7 35. 12 3 4 5 6 7 35. 12 3 4 5 6 7 36. 12 3 4 5 6 7 3 30. 12 3 4 5 6 7 3 30. 12 3 4 5 6 7 3 30. 12 3 4 5 6 7 3 30. 12 3 4 5 6 7 3 30. 12 3 4 5 6 7 3 30. 12 3 4 5 6 7 3 30. 12 3 4 5 6 7 3 30. 12 3 4 5 6 7 3 30. 12 3 4 5 6 7 3 30. 12 3 4 5 6 7 3 30. 12 3 4 5 6 7 3 30. 12 3 4 5 6 7		(5	≥80					
26. 1 2 3 4 5 6 7  27. 1 2 3 4 5 6 7  30. 1 2 3 4 5 6 7  31. 1 2 3 4 5 6 7  32. 1 2 3 4 5 6 7  33. 1 2 3 4 5 6 7  36. 1 2 3 4 5 6 7  36. 1 2 3 4 5 6 7  37. 1 2 3 4 5 6 7  38. 1 2 3 4 5 6 7  39. 1 2 3 4 5 6 7  30. 1 2 3 4 5 6 7  31. 1 2 3 4 5 6 7  32. 1 2 3 4 5 6 7  33. 1 2 3 4 5 6 7  36. 1 2 3 4 5 6 7  36. 1 2 3 4 5 6 7  37. 1 2 3 4 5 6 7  38. 1 2 3 4 5 6 7  39. 1 2 3 4 5 6 7  30. 1 2 3 4 5 6 7  31. 1 2 3 4 5 6 7  32. 1 2 3 4 5 6 7  36. 1 2 3 4 5 6 7  36. 1 2 3 4 5 6 7  36. 1 2 3 4 5 6 7  36. 1 2 3 4 5 6 7  37. 1 2 3 4 5 6 7  38. 1 2 3 4 5 6 7  38. 1 2 3 4 5 6 7  39. 1 2 3 4 5 6 7  30. 1 2 3 4 5 6 7  30. 1 2 3 4 5 6 7  31. 1 2 3 4 5 6 7  32. 1 2 3 4 5 6 7  36. 1 2 3 4 5 6 7  37. 1 2 3 4 5 6 7  38. 1 2 3 4 5 6 7  38. 1 2 3 4 5 6 7  38. 1 2 3 4 5 6 7  38. 1 2 3 4 5 6 7  38. 1 2 3 4 5 6 7  38. 1 2 3 4 5 6 7  38. 1 2 3 4 5 6 7  38. 1 2 3 4 5 6 7  38. 1 2 3 4 5 6 7  38. 1 2 3 4 5 6 7  38. 1 2 3 4 5 6 7  38. 1 2 3 4 5	Additional statements or questions which may be suppli	ied in cla	ass:					
27. 1234567 30. 1234567 33. 1234567 36. 1234567  2ART II: PLEASE ANSWER ONLY AFTER COMPLETING PART I. Please use the space below to provide supplementary comment on the instructor(s) or course. For example, you may wish to give the reasons for your numerical evaluations or provide specific suggestions for improving the instruction in the course.  - The does not mark assignments fairly  - Professor loses his train of thought quite often  - He is von enthusiastic about the naterial in class  - Exams are extremely difficult compared to the neckly  assignments	25. 1 2 3 4 5 6 7 28. 1 2 3 4 5 6 7 26. 1 2 3 4 5 6 7	31. (1 32. (1						
on the instructor(s) or course. For example, you may wish to give the reasons for your numerical evaluations or provide specific suggestions for improving the instruction in the course.  - The closes not mark assignments fairly  Professor loses his train of thought quite often  - He is vary enthusiastic about the naterial in class  - Exams are extremely difficult compared to the neckly  assignments								
on the instructor(s) or course. For example, you may wish to give the reasons for your numerical evaluations or provide specific suggestions for improving the instruction in the course.  - The closes not mark assignments fairly  Professor loses his train of thought quite often  - He is vary enthusiastic about the naterial in class  - Exams are extremely difficult compared to the neekly  assignments	PART II. DI FASE ANSWED ONI V AFTED COMDI ETING DADT	I Dlagge v	so the sp	aga balarri	+0 marrid		- o to to to to	
- TA does not mark assignments fairly  Professor loses his train of thought quite often  - He is vary enthusiastic about the naterial in class  - Exams are extremely difficult compared to the neckly assignments								
- Exams are extremely difficult compared to the needly assignments	suggestions for improving the instruction in the course		5			•	1	
- Exams are extremely difficult compared to the needly assignments	In last the use assignment	ute to	virly					
- Exams are extremely difficult compared to the neckly assignments	- IFF does not mark asignite				,			
- Exams are extremely difficult compared to the neckly assignments	· Professor loses his train of the	ought	qui	ite oft	en			
- Exams are extremely difficult compared to the neckly assignments	- He is very enthusiastic about	the	meter	rial in	clas.	5		
assignments	- Exams are extremely difficult	1 con	pane	d to	the	necki	ly	
- Material is not useful in real life.	assignments							
	- Material is not useful in n	eal 1	ife.					

**UNIVERSITY OF TORONTO** 



Note that survey results will be available to the instructor(s) only after final course marks have been submitted.

### PART I: INSTRUCTIONS. PLEASE READ FIRST.

Using an HB pencil or a blue or black ball-point pen (but not a felt marking pen), fill completely the numbered oval corresponding to your response for each statement. If using a pen, do not alter original response by making another selection.

Part II (on the reverse side) requires a written answer.

Course Identification: Please print course and section you are evaluating

COURSE MATHOLHIS	SECTION L 5 1 0 1	INSTRUCTOR(S):
If evaluating only one instructor, write the na two instructors, write their names, one in box		A: Draw Bar-Norton B:
DO NOT EVALUATE TEACHING AS	SISTANTS ON THIS FORM	
Statements about the instructor(s):	or A (and instructor B) bearing in mi	nd that there are wide variations in class size

and subject matter in Arts and Science.

		extremely poor	very poor	poor	adequate	good	very	outstanding
2.	Communicates goals and requirements of the course clearly	A: ①	(2)	(3)	<b>(4)</b>	(5)	<b>(</b>	(7)
	and explicitly	B: 1	(2)	(3)	(4)	(5)	6	(7)
3.	Uses methods of evaluation (e.g. papers, assignments, tests) that appropriately reflect the subject matter and provide a fair evaluation	Б. 🕕		(3)	•			•
	of student learning	A: 1	2	(3)	4	(5)	<b>(4)</b>	7
	-	B: ①	(2)	3	4	(5)	6	(7)
4.	Presents material in an organized, well-planned manner	A: 1	(2)	(3)	4	(3)	(6)	(7)
		B: ①	(2)	(3)	(4)	(5)	6	7
5.	Explains concepts clearly with appropriate use of examples	A: 1	(2)	(3)	4		6	(7)
٠.		B: ①	(2)	(3)	4	(5)	(6)	(7)
6.	Communicates enthusiasm and interest in the course material		(2)	(3)	4	(5)	(6)	<b>@</b>
		B: 1	(2)	(3)	4	(5)	6	(7)
7.	Attends to students' questions and answers them clearly	Λ. (1)	(2)	(3)	(4)	(5)	(EA)	(7)
	and effectively.	B: 1	(2)	(3)	(4)	(5)	6	(7)
Ω	Is available for individual consultation, by appointment or stated	<b>D.</b>		(0)		(0)	(0)	
0.	office hours, to students with problems relating to the course	. A: ①	(2)	(3)	(4)	(5)	(6)	
	onico necio, to citatoria mar prosionio rotating to the ocurrent	B: 1	2	(3)	(4)	(5)	(6)	(7)
9.	Ensures that student work is graded fairly, with helpful comments							
	and feedback where appropriate	A: 1	2	(3)	4	(5)	(4)	7
		B: ①	(2)	(3)	4	(5)	6	(7)
10.	Ensures that student work is graded within a reasonable time	A: ①	(2)	(3)	4	(5)	(6)	
		B: 1	(2)	(3)	4	(5)	6	(7)
11.	All things considered, performs effectively as a university teacher	A: 1	2	(3)	4	(5)	(6)	@
		B. 1	(2)	(3)	(4)	(5)	(6)	(7)

		1						803		
Statements about the co	urse: Respon	nd to the state	ments below,	using th	e follow	ving 7-poi	nt scale.		9	SIDE 2
12. Compared to other course	s at the same I	evel (100.200.3	00.400). the	very low	low	below average	average	above average	high	very high
work load is	s at the same I	evel, the level of	of difficulty of		(2)	(3)		5	6	7)
the material is					2	(3)	(4)	(5)		7
<ul><li>14. The value of the required r</li><li>15. (If applicable) The value of</li></ul>					2	(3)	4	(5)	(6) (6)	(7) (7)
16. (If applicable) The value of	the laboratoric	es is		. 0	(2)	(3)	4	(5)	6	7
17. (If applicable) The value of 18. (If applicable) The value of					2	(3)	4	5	6	7
19. The value of the overall lea	arning experier	nce is		1	2	(3)	4		6	(7)
20. Considering your experien meet program or degree re	ice with this co equirements, w	ourse, and disre ould you still h	egarding your ave taken this	need for i course?	t to	Ye	s	O No		
Statements about yourse  21. Number of full course cree  1 0-41/2 2 5-9  22. Status of the course for your service of the your service of the your service of your service of the your service of your service of your service of your service of your s	dits already early 3 ou: 2 Select take this coudium 3 is course:	10-14½ ted from a requi irse at the time high	15-19½ red list in a proof initial regis	gram	≥20 ③ B	Freadth Req	uirement	(4)	Optional	
1) <50 (2) 50-5	59 ③	60-69	20-79	(5)	≥80					
Additional statements o				d in cla	ss:					
25. 1 2 3 4 5 6 7 26. 1 2 3 4 5 6 7		2 3 4 5 6				5 6 7				(5) (6) (7) (5) (6) (7)
27. 1 2 3 4 5 6 7		2 3 4 5 6				5 6 7				5 6 7
suggestions for improving the  Brow prese  Cuthus  topics  the	ion and		mola le	eve	moni	ner, hi	s the			
	emely	the last districult of hac	t, there	jh # ]	I'm	not s	we	<i>-</i> }		
	Cucart	- Cans	e & C	week	Pate	eque	. !			





INSTRUCTOR(S):

Dross

B:

Bar-Natan

Note that survey results will be available to the instructor(s) only after final course marks have been submitted.

### PART I: INSTRUCTIONS. PLEASE READ FIRST.

Using an HB pencil or a blue or black ball-point pen (but not a felt marking pen), fill completely the numbered oval corresponding to your response for each statement. If using a pen, do not alter original response by making another selection.

**SECTION** 

Part II (on the reverse side) requires a written answer.

**COURSE** 

Course Identification: Please print course and section you are evaluating

 If evaluating only one instructor, write the name in the upper (A) box. If evaluating two instructors, write their names, one in box A and the other in box B.

	DO NOT EVALUATE TEACHING ASSISTANTS ON THIS FO	RM						
Sta	tements about the instructor(s):							
	spond to the statements below for instructor A (and instructor B) I subject matter in Arts and Science.	bearing in	n mind t	hat ther	e are wide	variatio	ns in cla	ass size
		extremely poor	very poor	poor	adequate	good	very good	outstanding
2.	Communicates goals and requirements of the course clearly and explicitly.	A: 1	2	3	4	•	6	(7)
		B: 1	(2)	(3)	4	(5)	6	7
3.	Uses methods of evaluation (e.g. papers, assignments, tests) that appropriately reflect the subject matter and provide a fair evaluation							
	of student learning.		2	•	4	(5)	(6)	7
		B: 1	2	3	(4)	(5)	6	(7)
4.	Presents material in an organized, well-planned manner		2	(3)	4	0	(6)	(7) (7)
		B: 1	2	3	4	(5)	(6)	(7)
5.	Explains concepts clearly with appropriate use of examples	A: 1	2	(3)	4		6	7
		B: 1	(2)	3	4	(5)	(6)	7
6.	Communicates enthusiasm and interest in the course material	A: 1	2	(3)	4	(5)		(7)
		B: 1	(2)	(3)	4	(5)	(6)	7
7.	Attends to students' questions and answers them clearly					-		
	and effectively	A: 1 B: 1	(2)	(3)	(4)	(5)	6	7
Ω	Is available for individual consultation, by appointment or stated	D. <u>U</u>	(2)	(3)	4	(3)	0	
0.	office hours, to students with problems relating to the course	A: 1	2	(3)	4		6	(7)
		B: 1	2	(3)	4	5	6	7
9.	Ensures that student work is graded fairly, with helpful comments	246						
	and feedback where appropriate		(2)	(3)	(4)	(5)	(6)	(7)
		B: 1	(2)	(3)	(4)	(5)	6	
10.	Ensures that student work is graded within a reasonable time	A: 1	(2)	(3)	4	(5)	(6)	<b>@</b>
		D. (1)	(0)	(2)	(A)	/F)	(0)	(19)

PART I CONTINUES ON THE REVERSE SIDE

11. All things considered, performs effectively as a university teacher. ...

Statem	ents abo	out the co	ourse:	Respon	nd to the s	statements belov	v, using the	e follow	ing 7-poi	nt scale.			SIDE 2
							very low	low	below	average	above	high	very high
wor	k load is .					00,300,400), the		(2)	average	4	average	•	high
the	material is						1	(2)	(3)	4	(5)		7
								2	3	4	5	6	7
(If a	pplicable) 7	The value of	f the lab	oratorie	es is		1	(2)	(3)	4	5	6	7
						on classes is		2	(3)	4	(5)	6	7
						on classes is		2	3	4	5	6	7
Con	sidering yo	our experier	nce with	this co	urse, and c	disregarding you till have taken thi	need for it	to	Ye	s	O No		
. Nur	nber of full 0-4½ tus of the c Program Re	2 5-9 course for ye equirement	dits alre	3) 2) Select	10-14½ ted from a r	to this session):  15-19½ required list in a pr	ogram	≥20 ③ B	readth Req	uirement	<b>(4</b> )	Optional	
You	low	2 me I grade in th 2 50-	dium iis cours	se:	high 60-69	<b>→</b> 70-79		≥80					
	onal stat		or que		which n	nay be suppli			(5) (6) (7)		34 (1)	(2)(3)(4)	5 6
	2 3 4 5				2 3 4				5 6 7			2 3 4	
. 1	2 3 4 5	5 (6) (7)		30 (4)	10 10 10 1			2 3 4	5 6 7		36. 🕦		5 6
the i	nstructor(s	ANSWER	. For ex	AFTEF	R COMPL you may v	LETING PART I	. Please us	e the sp	ace below				
the i	nstructor(s ons for im	ANSWER s) or course	e. For ex e instru	AFTER cample, action in	R COMPL you may v	LETING PART I	. Please use reasons for	e the spa your nu	ace below merical ev	aluations	or provid	nentary o	С
the i	nstructor(s ons for im	ANSWER s) or course	e. For ex e instru	AFTER cample, action in	R COMPL you may v	LETING PART I	. Please use reasons for	e the spa your nu	ace below merical ev	aluations	or provid	nentary o	С
the i	nstructor(s ons for im	ANSWER s) or course	e. For ex e instru	AFTER cample, action in	R COMPL you may v	LETING PART I	. Please use reasons for	e the spa your nu	ace below merical ev	aluations	or provid	nentary o	С
the i	nstructor(s ons for im	ANSWER s) or course	e. For ex e instru	AFTER cample, action in	R COMPL you may v	LETING PART I	. Please use reasons for	e the spa your nu	ace below merical ev	aluations	or provid	nentary o	С
the i	nstructor(s ons for im	ANSWER s) or course	e. For ex e instru	AFTER cample, action in	R COMPL you may v	LETING PART I	. Please use reasons for	e the spa your nu	ace below merical ev	aluations	or provid	nentary o	С
the i gesti	nstructor(s ons for im	ANSWER s) or course	e. For ex e instru	AFTER cample, action in	R COMPL you may v	LETING PART I	. Please use reasons for	e the spa your nu	ace below merical ev	aluations	or provid	nentary o	С
the i	nstructor(s ons for im	ANSWER s) or course	e. For ex e instru	AFTER cample, action in	R COMPL you may v	LETING PART I	. Please use reasons for	e the spa your nu	ace below merical ev	aluations	or provid	nentary o	С
the i	nstructor(s ons for im	ANSWER s) or course	e. For ex e instru	AFTER cample, action in	R COMPL you may v	LETING PART I	. Please use reasons for	e the spa your nu	ace below merical ev	aluations	or provid	nentary o	c
the i	nstructor(s ons for im	ANSWER s) or course	e. For ex e instru	AFTER cample, action in	R COMPL you may v	LETING PART I	. Please use reasons for	e the spa your nu	ace below merical ev	aluations	or provid	nentary o	с
the i	nstructor(s ons for im	ANSWER s) or course	e. For ex e instru	AFTER cample, action in	R COMPL you may v	LETING PART I	. Please use reasons for	e the spa your nu	ace below merical ev	aluations	or provid	nentary o	с
the i	nstructor(s ons for im	ANSWER s) or course	e. For ex e instru	AFTER cample, action in	R COMPL you may v	LETING PART I	. Please use reasons for	e the spa your nu	ace below merical ev	aluations	or provid	nentary o	c
the i	nstructor(s ons for im	ANSWER s) or course	e. For ex e instru	AFTER cample, action in	R COMPL you may v	LETING PART I	. Please use reasons for	e the spa your nu	ace below merical ev	aluations	or provid	nentary o	С
the i	nstructor(s ons for im	ANSWER s) or course	e. For ex e instru	AFTER cample, action in	R COMPL you may v	LETING PART I	. Please use reasons for	e the spa your nu	ace below merical ev	aluations	or provid	nentary o	С
the i	nstructor(s ons for im	ANSWER s) or course	e. For ex e instru	AFTER cample, action in	R COMPL you may v	LETING PART I	. Please use reasons for	e the spa your nu	ace below merical ev	aluations	or provid	nentary o	С
the i	nstructor(s ons for im	ANSWER s) or course	e. For ex e instru	AFTER cample, action in	R COMPL you may v	LETING PART I	. Please use reasons for	e the spa your nu	ace below merical ev	aluations	or provid	nentary o	С
the i	nstructor(s ons for im	ANSWER s) or course	e. For ex e instru	AFTER cample, action in	R COMPL you may v	LETING PART I	. Please use reasons for	e the spa your nu	ace below merical ev	aluations	or provid	nentary o	С
the i	nstructor(s ons for im	ANSWER s) or course	e. For ex e instru	AFTER cample, action in	R COMPL you may v	LETING PART I	. Please use reasons for	e the spa your nu	ace below merical ev	aluations	or provid	nentary o	С
the i	nstructor(s ons for im	ANSWER s) or course	e. For ex e instru	AFTER cample, action in	R COMPL you may v	LETING PART I	. Please use reasons for	e the spa your nu	ace below merical ev	aluations	or provid	nentary o	С
the i	nstructor(s ons for im	ANSWER s) or course	e. For ex e instru	AFTER cample, action in	R COMPL you may v	LETING PART I	. Please use reasons for	e the spa your nu	ace below merical ev	aluations	or provid	nentary o	С



**INSTRUCTOR(S):** 

Note that survey results will be available to the instructor(s) only after final course marks have been submitted.

### PART I: INSTRUCTIONS. PLEASE READ FIRST.

Using an HB pencil or a blue or black ball-point pen (but not a felt marking pen), fill completely the numbered oval corresponding to your response for each statement. If using a pen, do not alter original response by making another selection.

Part II (on the reverse side) requires a written answer.

Course Identification: Please print course and section you are evaluating

COURSE MATHOLINIS SECTION (5)

6. Communicates enthusiasm and interest in the course material. . . . . . A: 1

7. Attends to students' questions and answers them clearly

10. Ensures that student work is graded within a reasonable time. . . . . .

11. All things considered, performs effectively as a university teacher. ...

and effectively. . . . .

1.	If evaluating only one instructor, write the name in the upper (A) box. I	If evaluatir	ng [	A: Dr	or [	3ar-1	Vato	27
	two instructors, write their names, one in box A and the other in box B		_	B:				
	DO NOT EVALUATE TEACHING ASSISTANTS ON THIS FO	RM						,
ita	tements about the instructor(s):							
	pond to the statements below for instructor A (and instructor B)	bearing in	n mind	that ther	e are wide	variatio	ns in cl	ass size
ınd	l subject matter in Arts and Science.							
		extremely poor	very poor	poor	adequate	good	very good	outstandin
2.	Communicates goals and requirements of the course clearly	A : (1)	(2)	(3)	4		(6)	7)
	and explicitly.	A: 1 B: 1	(2)	(3)	(4)	(5)	(6)	(7)
3.	Uses methods of evaluation (e.g. papers, assignments, tests) that appropriately reflect the subject matter and provide a fair evaluation							
	of student learning.	A: 1	(2)	(3)		(5)	(6)	7
		B: 1	(2)	(3)	4	(5)	6	(7)
4.	Presents material in an organized, well-planned manner	A: 1	2	(3)	4	6	6	(7)
		B: 1	(2)	(3)	4	(5)	(6)	(7)
5.	Explains concepts clearly with appropriate use of examples	A: 1	(2)	(3)		(5)	6	7
		B: 1	2	(3)	4	(5)	6	(7)

A: 1

B: 1

A: 1

Statements about the course: Respond to the statements below	, using th	e follow	ing 7-poi	nt scale.			SIDE 2
12. Compared to other courses at the same level (100,200,300,400), the	very low	low	below average	average	above average	high	very high
work load is	. ①	2	3	4		6	7
Compared to other courses at the same level, the level of difficulty of the material is	. 1	(2)	(3)	4		6	7
14. The value of the required reading is	① ①	(2)	(3)	4	(5)	6	7
16. (If applicable) The value of the laboratories is	. 1	(2)	3	4	5	6	7
18. (If applicable) The value of the language conversation classes is	. ①	(2)	(3)	4	(5)	6	7
<ol> <li>The value of the overall learning experience is</li> <li>Considering your experience with this course, and disregarding your</li> </ol>	need for i	t to	3		5	6	(7)
meet program or degree requirements, would you still have taken this	course?		◆ Ye	S	O No		
Statements about yourself:  21. Number of full course credits already earned (prior to this session):  1 0-4½ 2 5-9½ 3 10-14½ 4 15-19½ 2 Status of the course for you:  1 Program Requirement Selected from a required list in a program level of enthusiasm to take this course at the time of initial regism low 1 low medium 3 high 24. Your expected grade in this course: 1 <50 2 50-59 60-69 4 70-79	gram tration:	≥20 3 B	readth Req	uirement	4)	Optional	
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ART II: PLEASE ANSWER ONLY AFTER COMPLETING PART I. on the instructor(s) or course. For example, you may wish to give the remarks the state of the s							
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# STUDENT SURVEY FORM





Note that survey results will be available to the instructor(s) only after final course marks have been submitted.

#### PART I: INSTRUCTIONS. PLEASE READ FIRST.

Using an HB pencil or a blue or black ball-point pen (but not a felt marking pen), fill completely the numbered oval corresponding to your response for each statement. If using a pen, do not alter original response by making another selection.

Part II (on the reverse side) requires a written answer.

Course Identification: Please print course and section you are evaluating

COURSE M A T 4 0 1 H 1 5	SECTION LS 101	INSTRUCTOR(S):
I. If evaluating only one instructor, write the n two instructors, write their names, one in bo	A: Dror Bar-Natan B:	
DO NOT EVALUATE TEACHING A	SSISTANTS ON THIS FORM	

# Statements about the instructor(s):

Respond to the statements below for instructor A (and instructor B) bearing in mind that there are wide variations in class size and subject matter in Arts and Science.

		extremely poor	very poor	poor	adequate	good	very good	outstanding
2.	Communicates goals and requirements of the course clearly		-		-	enth.	(0)	/ <del></del>
	and explicitly.		(2)	3	4	(5)	(6)	(7)
3.	Uses methods of evaluation (e.g. papers, assignments, tests) that appropriately reflect the subject matter and provide a fair evaluation	B: 1	(2)	(3)	4)	3	0	· ·
	of student learning	A: 1	(2)	(3)	(4)	60	(6)	7
		B: 1	2	(3)	4	(5)	6	7
4.	Presents material in an organized, well-planned manner	A: 1	2	(3)		5	6	7
		B: 1	2	3	4	(5)	6	7
5. Explains concepts clearly with	Explains concepts clearly with appropriate use of examples	A: 1	(2)	(3)		(5)	(6)	(7)
		B: ①	(2)	3	4	(5)	6	7
6.	Communicates enthusiasm and interest in the course material	A: 1	(2)	(3)	4		6	7
		B: 1	(2)	(3)	4	(5)	(6)	7
7.	Attends to students' questions and answers them clearly							
	and effectively.		2	(3)	<b>(</b>	(5)	(6)	7
		B: 1	(2)	(3)	4	(5)	6	(7)
8.	Is available for individual consultation, by appointment or stated	A . (T)		/ 0	47800	(5)	(6)	(9)
	office hours, to students with problems relating to the course	A: 1 B: 1	(2)	(3)	(4)	(5)	(6)	(7)
0	Ensures that student work is graded fairly, with helpful comments	<b>D</b> : <b>U</b>	(2)	(9)	(4)	(3)	(0)	
9.	and feedback where appropriate	A: ①	(2)	(3)		(5)	(6)	(7)
and reed	and recastor where appropriates	B: 1	(2)	(3)	(4)	(5)	(6)	(7)
10.	Ensures that student work is graded within a reasonable time	A: 1	(2)	(3)	4	•	(6)	. (7)
		B: ①	(2)	(3)	4	(5)	(6)	7
11.	All things considered, performs effectively as a university teacher	A: 1	(2)	(3)	(90)	(5)	(6)	(7)
• • •		B: 1)	(2)	(3)	(4)	(5)	(6)	(7)

PART I CONTINUES ON THE REVERSE SIDE

Statements about the course								
ratements about the course	: Respond to the statements below,	using the	follow	ing 7-poi	nt scale.		3	SIDE 2
12. Compared to other courses at the	ne same level (100 200 200 400) +ba	very low	low	below average	average	above average	high	very high
work load is	ne same level, the level of difficulty of	1	2	3	0	5	6	7
the material is			(2)	(3)	4	(5)	-	(7)
	g is utorials is		(2)	(3)	4	(5)	(6) (6)	7
<ol><li>(If applicable) The value of the la</li></ol>	aboratories is	. O	(2)	(3)	4	(5)	(6)	7
	eminars is		(2)	3	(4)	5	6	7
9. The value of the overall learning	experience is	①	(2)		4	5	6	(7)
	th this course, and disregarding your ments, would you still have taken this		to	C Ye	S	No		
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Two What Finish verly Return HW9. Z. V fix so cond. Math 401 Pols Egns Fields, April 9 2008, Week 13 (last) I on The Final. on boald: for asplitting ext. E 2. Fix blunder. E COLFE) 3. state Lemms. KETHOLEKON EFRICALLE 4. Prost of You = t 5. Prost of Lymns. F ( ) 6 - Cal (E/F) - 6d(E/F)/6d(E/K) Flan. an FEn (F) Blunder - Kz=SEalf) Flagar)CEZ Ko=SE(F) emmaz yningness of J: K -> Gal (E/K) Splitting Fields Lemma & Splitting Fills Y: HHD EH are good at splitting Claim Yo D=I, OF EGOLETA K Prost E: 35 - JE Prot of longs Proof of Jammy F(W) D > Fz/Uz) F, \$\frac{\psi}{F\_2} \frac{1}{F\_2} \frac{1}{ F(w) w another

# 08-401/The Final Exam

# From Drorbn

08-401/Navigation Panel [Show] As announced (http://www.artsci.utoronto.ca/current/undergraduate/exams/aprmay08) by the powers above, our final exam will take place on the evening of Monday April 28 between 7PM and 10PM, at BN2S (Large Gymnasium, South End, Benson Building, 320 Huron Street (south of Harbord Street), Second Floor).

The exam will be similar in style to the Term Test (also see On the Term Test), and perhaps even more similar in style to last years' final (PDF). The material is everything covered in class. There will be two types of questions (or maybe sometimes the two types will be mixed within a single question):

■ You may be asked to prove a theorem proven in class. The reason we prove theorems in class is that these proofs are valuable. Therefore I expect you to know them.

■ You may be asked to solve exercises from the relevant chapters of the book, or minor variations thereof. These may be questions that were assigned as homework, but also, these may be questions that were not assigned before.

Office Hours. I (Dror) will hold extended office hours before the final, on Friday April 25 1-4PM and on the exam date, Monday April 28 10AM-12PM, at or near my office, Bahen 6178.

Preparing for the Test. Read, reread and rereread everything and solve lots of exercises from the book.

My (Dror's) system when I was an undergrad was to prepare a 4-6 page 100-200 item list of points covered in class. I'd only summarize each point with one sentence, without giving any details and without trying to be precise, much like the list that I prepared for the class of February 7 (see On the Term Test). I would then go over my list again and again and again, crossing out every item for which I was sure I could complete all the details and supply all the proofs. I would only stop when there was nothing left to cross out.

# Good Luck!

Retrieved from "http://katlas.math.toronto.edu/drorbn/index.php?title=08-401/The\_Final\_Exam"

■ This page was last modified 14:54, 9 April 2008.

# UNIVERSITY OF TORONTO

Faculty of Arts and Sciences APRIL-MAY EXAMINATIONS 2007 Math 401H1S Polynomial Equations and Fields

Instructor: Dror Bar-Natan Date: April 24, 2007

**Duration.** You have 3 hours to write this exam.

Allowed Material. Basic calculators, not capable of displaying text or sounding speech.

Solve 6 of the following 7 questions. The questions carry equal weight though different parts of the same question may be weighted differently.

Neatness counts! Language counts! The *ideal* written solution to a problem looks like a proof from the textbook; neat and clean and made of complete and grammatical sentences. Definitely phrases like "there exists" or "for every" cannot be skipped. Lectures are mostly made of spoken words, and so the blackboard part of proofs given during lectures often omits or shortens key phrases. The ideal written solution to a problem does not do that.

# Good Luck!

Solve 6 of the following 7 problems. Neatness counts! Language counts!

**Problem 1.** Let R be a commutative ring with unity and let A be an ideal of R. Prove that R/A is a field if and only if A is maximal.

**Problem 2.** Let  $\mathbb{Z}[\sqrt{2}] = \{a + b\sqrt{2}|a,b \in \mathbb{Z}\}$  and let  $H = \left\{ \begin{pmatrix} a & 2b \\ b & a \end{pmatrix} \middle| a,b \in \mathbb{Z} \right\}$ . Show that  $\mathbb{Z}[\sqrt{2}]$  and H are isomorphic as rings. (Remember that in math-talk the word "show" is equivalent to the word "prove".)

Kemember that in math-talk the word show is equivalent to the word prove of

**Problem 3.** Let  $f(x) = x^3 + 6 \in \mathbb{Z}_{\ell}[x]$ . Write f(x) as a product of irreducible polynomials over  $\mathbb{Z}_{\ell}$ . (Remember to explain why each of the factors you end up writing really is irreducible!)

**Problem 4.** Let E/F be a field extension and let  $a \in E$  satisfy p(a) = 0 where  $p \in F[x]$  is a polynomial with coefficients in F. Define the field F(a) and prove that it is isomorphic to the field  $F[x]/\langle p(x) \rangle$ .

**Problem 5.** Let E/F be a field extension and let a and b be elements of the bigger field E.

- 1. Show that [F(a):F] is finite if and only if a is algebraic over F.
- 2. Prove that if both a and b are algebraic over F, then so is a+b.

**Problem 6.** Show that the Galois group of a polynomial of degree n (i.e., of the splitting field of a polynomial of degree n over some base field) has order dividing n!.

**Problem 7.** Let F be the field  $\mathbb{Q}(i)$  and let E be the field  $\mathbb{Q}(\sqrt[4]{2}, i)$ .

- 1. Compute G := Gal(E/F).
- 2. Find all the subgroups H of G.
- 3. For exactly one non-trivial subgroup of G (that is, a subgroup that is neither  $\{e\}$  nor G), describe the fixed field  $E_H$ .

(The word "describe" here means "find  $a \in E$  so that  $E_H = F(a)$ ".)

# Good Luck!

Math 401 Pols, Egns, Fields, April 2 2008, Week 12 tomorrow. on board IF E/F a splitting city is and Stield ext > Sgroups Jext by radially > Ssolvable? Sa(3x5-15x+5) > S5 (solvable) ek: E/R/Fy &> (H: H< Gal [E/F]) K H > Cal(E/K) EHETH 1. inclusion reversing > dey = and (E/E) If k is splitting, 1171 and GD(K/F)=G/H = GD(E/F)/ GD(E/K) > H = Gal(E/K) | & [G:H] >> G = Gal(E/F) "If E is the splitting ticked
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Math 40/ Pols Egns, Fields, Week 12 cont. Thm 6/5@(3x5-15x+5)/2)=5=5, GCS5,
Proof (Pish irred =) [(x):0]=5=) 5 [E:0] =75/16/ => 6 has an element of order 5. 2. By drawing, P has exactly \$ real rosts => 2 complex

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# 08-401/The Fundamental Theorem

# From Drorbn

The statement appearing here, which is a weak version of the full fundamental theorem 08-401/Navigation Panel [Hide] of Galois theory, is taken from Gallian's book and is meant to match our discussion in class. The proof is taken from Hungerford's book, except modified to fit our notations and conventions and simplified as per our weakened requirements.

Here and everywhere below our base field F will be a field of characteristic 0.

# **Contents**

- 1 Statement
- 2 Lemmas
  - 2.1 Zeros of Irreducible Polynomials
  - 2.2 Uniqueness of Splitting Fields
  - 2.3 The Primitive Element Theorem
  - 2.4 Splitting Fields are Good at Splitting
- 3 Proof of The Fundamental Theorem
  - 3.1 The Bijection
  - 3.2 The Properties

#	Week of	Links				
1	Jan 9	About, Notes, HW1				
2	Jan 16	HW2, Notes				
3	Jan 23	HW3, Photo, Notes				
4	Jan 30	HW4, Notes				
5	Feb 6	HW5, Notes				
6	Feb 13 On TT, Notes					
R	R Feb 20 Reading week					
7						
8	Mar 5	HW6, Notes				
9	Mar 12	HW7, Notes				
10	Mar 19 HW8, Notes, RC (PDF)					
11	Mar 26	HW9, Notes				
12	Apr 2	FT, HW10, Notes				
13	Apr 9	Notes				
S	Apr 14-18	Study Period				
F	Apr 28	Final				
	Add your	name / see who's in!				
		er of Good Deeds				

# Statement

**Theorem.** Let E be a splitting field over F. Then there is a bijective correspondence between the set  $\{K: E/K/F\}$  of intermediate field extensions K lying between F and E and the set  $\{H: H < \operatorname{Gal}(E/F)\}$  of subgroups H of the Galois group Gal(E/F) of the original extension E/F:

$$\{K: E/K/F\} \quad \leftrightarrow \quad \{H: H < \operatorname{Gal}(E/F)\} \, \cdot \,$$

The bijection is given by mapping every intermediate extension K to the subgroup  $\mathrm{Gal}(E/K)$  of elements in Gal(E/F) that preserve K,

$$\Phi: \quad K \mapsto \operatorname{Gal}(E/K) := \{\phi : E \to E : \phi|_K = I\},\$$

and reversely, by mapping every subgroup H of Gal(E/F) to its fixed field  $E_H$ :

$$\Psi: \quad H \mapsto E_H := \{ x \in E : \forall h \in H, \ hx = x \} .$$

This correspondence has the following further properties:

- 1. It is inclusion-reversing: if  $H_1 \subset H_2$  then  $E_{H_1} \supset E_{H_2}$  and if  $K_1 \subset K_2$  then  $\operatorname{Gal}(E/K_1) > \operatorname{Gal}(E/K_2)$ .
- 2. It is degree/index respecting:  $[E:K] = |\operatorname{Gal}(E/K)|$  and  $[K:F] = [\operatorname{Gal}(E/F):\operatorname{Gal}(E/K)]$ .
- 3. Splitting fields correspond to normal subgroups: If K in E/K/F is the splitting field of a polynomial in F[x] then  $\operatorname{Gal}(E/K)$  is normal in  $\operatorname{Gal}(E/F)$  and  $\operatorname{Gal}(K/F) \cong \operatorname{Gal}(E/F)/\operatorname{Gal}(E/K)$ .

$$E \iff delg = Gal(E/E)$$

$$|E:K] \qquad |H||$$

$$|K \iff H = Gal(E/K)) \text{ If } K \text{ is splitting,}$$

$$|K:F] \qquad |G:H| \qquad |Gal(K/F) = G/H$$

$$|E \iff G = Gal(E/F)| = Gal(E/F)/Gal(E/K)$$

The Fundamental Theorem of Galois Theory, all in one.

# Lemmas

The four lemmas below belong to earlier chapters but we skipped them in class (the last one was also skipped by Gallian).

# Zeros of Irreducible Polynomials

Lemma 1. An irreducible polynomial over a field of characteristic 0 has no multiple roots.

**Proof.** See the proof of Theorem 20.6 on page 362 of Gallian's book. □

# **Uniqueness of Splitting Fields**

**Lemma 2.** Let  $\phi: F_1 \to F_2$  be an isomorphism of fields, let  $f_1 \in F_1[x]$  be a polynomial and let  $f_2 = \phi(f_1)$ , and let  $E_1$  and  $E_2$  be splitting fields for  $f_1$  and  $f_2$  over  $F_1$  and  $F_2$ , respectively. Then there is an isomorphism  $\bar{\phi}: E_1 \to E_2$  (generally not unique) that extends  $\phi$ .

**Proof.** See the proof of Theorem 20.4 on page 360 of Gallian's book. □

#### The Primitive Element Theorem

The celebrated "Primitive Element Theorem" is just a lemma for us:

**Lemma 3.** Let a and b be algebraic elements of some extension E of F. Then there exists a single element c of E so that F(a,b)=F(c). (And so by induction, every finite extension of E is "simple", meaning, is generated by a single element, called "a primitive element" for that extension).

**Proof.** See the proof of Theorem 21.6 on page 375 of Gallian's book. □

# **Splitting Fields are Good at Splitting**

**Lemma 4.** (Compare with Hungerford's Theorem 10.15 on page 355). If E is a splitting field of some polynomial f over F and some irreducible polynomial  $p \in F[x]$  has a root v in E, then P splits in E.

**Proof.** Let L be a splitting field of p over E. We need to show that if w is a root of p in L, then  $w \in E$  (so all the roots of p are in E and hence p splits in E). Consider the two extensions

$$E = E(v)/F(v)$$
 and  $E(w)/F(w)$ .

The "smaller fields" F(v) and F(w) in these two extensions are isomorphic as they both arise by adding a root of the same irreducible polynomial (P) to the base field F. The "larger fields" E=E(v) and E(w) in these two extensions are both the splitting fields of the same polynomial (f) over the respective "small fields", as E/F is a splitting extension for f and we can use the sub-lemma below. Thus by the uniqueness of splitting extensions (lemma 2), the isomorphism between F(v) and F(w) extends to an isomorphism between E=E(v) and E(w), and in particular these two fields are isomorphic and so [E:F]=[E(v):F]=[E(w):F]. Since all the degrees involved are finite it follows from the last equality and from [E(w):F]=[E(w):E][E:F] that [E(w):E]=1 and therefore E(w)=E. Therefore  $w\in E\cdot \Box$ 

**Sub-lemma.** If E/F is a splitting extension of some polynomial  $f \in F[x]$  and z is an element of some larger extension L of E, then E(z)/F(z) is also a splitting extension of f.

**Proof.** Let  $u_1, \ldots, u_n$  be all the roots of f in E. Then they remain roots of f in E(z), and since f completely splits already in E, these are all the roots of f in E(z). So

$$E(z) = F(u_1, \ldots, u_n)(z) = F(z)(u_1, \ldots, u_n),$$

and E(z) is obtained by adding all the roots of f to F(z).  $\square$ 

# **Proof of The Fundamental Theorem**

# The Bijection

**Proof of**  $\Psi \circ \Phi = I$ . More precisely, we need to show that if K is an intermediate field between E and F, then  $E_{\operatorname{Gal}(E/K)} = K$ . The inclusion  $E_{\operatorname{Gal}(E/K)} \supset K$  is easy, so we turn to prove the other inclusion. Let  $v \in E - K$  be an element of E which is not in K. We need to show that there is some automorphism  $\phi \in \operatorname{Gal}(E/K)$  for which  $\phi(v) \neq v$ ; if such a  $\phi$  exists it follows that  $v \notin E_{\operatorname{Gal}(E/K)}$  and this implies the other inclusion. So let p be the minimal polynomial of v over K. It is not of degree 1; if it was, we'd have that  $v \in K$  contradicting the choice of v. By lemma 4 and using the fact that E is a splitting extension, we know that p splits in E, so E contains all the roots of p. Over a field of characteristic 0 irreducible polynomials cannot have multiple roots (lemma 1) and hence p must have at least one other root; call it w. Since v and w have the same minimal polynomial over K, we know that K(v) and K(w) are isomorphic; furthermore, there is an isomorphism  $\phi_0: K(v) \to K(w)$  so that  $\phi_0|_K = I$  yet  $\phi_0(v) = w$ . But E is a splitting field of some polynomial f over F and hence also over K(v) and over K(w). By the uniqueness of splitting fields (lemma 2), the isomorphism  $\phi_0$  can be extended to an isomorphism  $\phi: E \to E$ ; i.e., to an automorphism of E but then  $\phi|_K = \phi_0|_K = I$  so  $\phi \in \operatorname{Gal}(E/K)$ , yet  $\phi(v) = w \neq v$ , as required.  $\square$ 

**Proof of**  $\Phi \circ \Psi = I$ . More precisely we need to show that if  $H < \operatorname{Gal}(E/F)$  is a subgroup of the Galois group of E over F, then  $H = \operatorname{Gal}(E/E_H)$ . The inclusion  $H < \operatorname{Gal}(E/E_H)$  is easy. Note that H is finite since we've proven previously that Galois groups of finite extensions are finite and hence  $\operatorname{Gal}(E/F)$  is finite. We will prove the following sequence of inequalities:

$$|H| \le |\operatorname{Gal}(E/E_H)| \le [E:E_H] \le |H|$$

This sequence and the finiteness of |H| imply that these quantities are all equal and since  $H < \operatorname{Gal}(E/E_H)$  it follows that  $H = \operatorname{Gal}(E/E_H)$  as required.

The first inequality above follows immediately from the inclusion  $H < \operatorname{Gal}(E/E_H)$ .

By the Primitive Element Theorem (Lemma 3) we know that there is some element  $u \in E$  so that  $E = E_H(u)$ . Let p be he minimal polynomial of u over  $E_H$ . Distinct elements of  $\operatorname{Gal}(E/E_H)$  map u to distinct roots of p, but p has exactly  $\deg p$  roots. Hence  $|\operatorname{Gal}(E/E_H)| \leq \deg p = [E:E_H]$ , proving the second inequality above.

Let  $\sigma_1, \ldots, \sigma_n$  be an enumeration of all the elements of H, let  $u_i := \sigma_i u$  (with u as above), and let f be the polynomial

$$f = \prod_{i=1}^{n} (x - u_i).$$

Clearly,  $f \in E[x]$ . Furthermore, if  $\tau \in H$ , then left multiplication by  $\tau$  permutes the  $\sigma_i$ 's (this is always true in groups), and hence the sequence  $(\tau u_i = \tau \sigma u_i)_{i=1}^n$  is a permutation of the sequence  $(u_i)_{i=1}^n$ , hence

$$\tau f = \prod_{i=1}^{n} (x - \tau u_i) = \prod_{i=1}^{n} (x - u_i) = f,$$

and hence  $f \in E_H[x]$ . Clearly f(u) = 0, so p|f, so  $[E:E_H] = \deg p \leq \deg f = n = |H|$ , proving the third inequality above.  $\square$ 

# The Properties

**Property 1.** If  $H_1 \subset H_2$  then  $E_{H_1} \supset E_{H_2}$  and if  $K_1 \subset K_2$  then  $Gal(E/K_1) > Gal(E/K_1)$ .

**Proof of Property 1.** Easy. □

Property 2.  $[E:K] = |\operatorname{Gal}(E/K)|$  and  $[K:F] = [\operatorname{Gal}(E/F):\operatorname{Gal}(E/K)].$ 

**Proof of Property 2.** If  $K = E_H$ , then  $|\operatorname{Gal}(E/K)| = |\operatorname{Gal}(E/E_H)| = [E:E_H] = [E:K]$  as was shown within the proof of  $\Phi \circ \Psi = I$ . But every K is  $E_H$  for some H, so  $|\operatorname{Gal}(E/K)| = [E:K]$  for every K between E and E. The second equality follows from the first and from the multiplicativity of the degree/order/index in towers of extensions and in towers of groups:

$$[K:F] = \frac{[E:F]}{[E:K]} = \frac{|\operatorname{Gal}(E/F)|}{|\operatorname{Gal}(E/K)|} = [\operatorname{Gal}(E/F) : \operatorname{Gal}(E/K)]. \quad \Box$$

**Property 3.** If K in E/K/F is the splitting field of a polynomial in F[x] then Gal(E/K) is normal in Gal(E/F) and  $Gal(K/F) \cong Gal(E/F)/Gal(E/K)$ .

**Proof of Property 3.** We will define a surjective (onto) group homomorphism  $\rho: \operatorname{Gal}(E/F) \to \operatorname{Gal}(K/F)$  whose kernel is  $\operatorname{Gal}(E/K)$ . This shows that  $\operatorname{Gal}(E/K)$  is normal in  $\operatorname{Gal}(E/F)$  (kernels of homomorphisms are always normal) and then by the first isomorphism theorem for groups, we'll have that  $\operatorname{Gal}(K/F) \cong \operatorname{Gal}(E/F)/\operatorname{Gal}(E/K)$ .

Let  $\sigma$  be in  $\operatorname{Gal}(E/F)$  and let u be an element of K. Let p be the minimal polynomial of u in F[x]. Since K is a splitting field, lemma 4 implies that p splits in K[x], and hence all the other roots of p are also in K. As  $\sigma(u)$  is a root of p, it follows that  $\sigma(u) \in K$  and hence  $\sigma(K) \subset K$ . But since  $\sigma$  is an isomorphism,  $[\sigma(K):F] = [K:F]$  and hence  $\sigma(K) = K$ . Hence the restriction  $\sigma|_K$  of  $\sigma$  to K is an automorphism of K, so we can define  $\rho(\sigma) = \sigma|_K$ .

Clearly,  $\rho$  is a group homomorphism. The kernel of  $\rho$  is those automorphisms of E whose restriction to K is the identity. That is, it is  $\operatorname{Gal}(E/K)$ . Finally, as E/F is a splitting extension, so is E/K. So every automorphism of K extends to an automorphism of E by the uniqueness statement for splitting extensions (lemma 2). But this means that  $\rho$  is onto.  $\square$ 

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■ This page was last modified 16:46, 2 April 2008.

HW & due Hw returne HW9 on wes soon. Cowse aduations? Math 401 Rls, Egn's, Fields, March 26 2008, Week 11 Man: 1. Shople graps

2. So 15n't solvable

3. Ext. by costical -> solvable graps

3. Ext. by costical -> solvable graps of Field exits ] = The > for rosp Late: 4. compute Gal (Sol3x 5 15x15)/Q) SQ(3x5-15x15) -> (So (non-sol)) 5. Prove the F.T. (2). Isomorphism that I. If \$:6, >62 then ker & & airy 2. IR NOHTG are NAG then G/H = G/N/H/N 3. H<6, NOG HNH = HNN

h\_=h\_2 n\_2 n\_1^{-1}

De solvable G: 3-to. Hn Eh] = [h.M]

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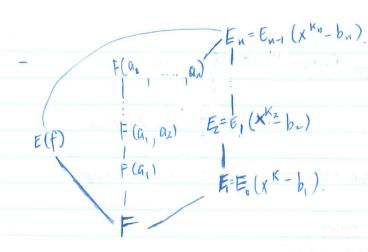
De solvable Eh] = [h.M] = [h.M]

h\_n = [h.M] = [h. HRTHK HK/dr. Abilian. Example: 1. Abelian Theorem If NOG, N&G/N solvable & G 15 solvable. PF = ) Circle North DHo-1. DHo=dey Holling abdian.

C/NEKMD. DKo=dety=SN3 D. OD Kei/Kin Abdian Consila 67 T (Km)># (Kn) ... >T (Ko)=N>Ha ... >Ho dain TI-1(ki) DT-1(ki) & 11 (K;)/11-(K;-1)=K;/K; (honco aboliki) 

Noth 40/ March 26 2008, Cont. Example Sy is solvable KA & cleanest DF \$: Sy >> S3 So Sy V ker\$ D \$ of C4 Theorems So is not solverle. 1 Consider A = of the subgroup gonated by 3-ryches). Lomma 1 [A,A]=A Lemma 2 IF H'AH", H"/H is Abulin My H">A, Then H'TEA, A) The two lemmas
prove the thornal NF of lemma / Consider [(isk), (kmn)] Back to theorem 1 = Assume & is solvable. G= HnVHn-1... Ho= Fey (Abel. Que) IF Imi: take HKN/N With G/N + Define out by + state solvable in HKN/N THEN SONG HK =) Solvesla grap. HKININ x Do the onge X-ATO, WFF.

V



- and E=F(xx-b) then Gal(E/F) is solvable
- CLAIM: Gal (Ex/F) is solvable for all K. In fact in any k-step toner of extensions, in which the Gal group is solvable, the whole toner is solvable.

PROOF

If k =1, this is the lemma.

G Ex-1 So Nable

By inductive hypothesis Gal (Ex/E,) is solvable and Gal (E,/E.) is solvable. E, is indeed a splitting extension

Let G=Gal (Ex/Eo), H=Gal (Ex/E,)

By property @, Gr/H = Gal (E, /Eo).

His solvable, G/H is solvable and therefore G is solvable

By & Gal(E(f)/F) is a quotient of Gal(E, /F), so it is solvable.

- E = F (x K-b)

```
- CASE O b=1
     F(x K-1) = F(w)
T. BEGAL (F(w)/F)
      o(w) = wi
     P. T = I : K is fall (E/K) - Emelows = K in = (W) I
   - CLAIM: If o, TEGAL (FLW)/F), then ot = To.
      PROOF
      Indeed, (OT)(w) = 5(T(w)) = 5(wi) = (O(w))i = (wi)i = wii
                 (\tau\sigma)(\omega) = \tau(\sigma(\omega)) = \tau(\omega) = (\tau(\omega))^{j} = (\omega^{i})^{j} = \omega^{ij}
                                        T. V. II H - E - CONCERS - H
   - CASED. b+1
       E= F(xk-b). ( ) ) how < H & book ( ) how > H & pass
              E = F(x^k - b) \ni \beta take \beta \in E at \beta^k = b.

Consider \omega \beta \in F(\beta, \omega).
       F(w)
        abelian F
                                                                              F(wiB)
      (wb) = w b = 1.b=b.
                                                                                 F(w)
      So was is a not of xh-b.
      So WBEE
     =>w= wB & E
   - CLAIM: Gal(F(x*-b)) /F(w)) is abelian.
      The mots of x^k - b are \beta, \omega^{\beta}, \omega^{\beta}, \dots, \omega^{k-1}\beta
F(x^k - b) = F(\omega)(\beta)
      if o, t = Gal (F(w)(x)/F(w)), then ot = to
     Indeed 5(B)=WB T(B) WB
     (\sigma \tau)(\beta) = \sigma(\tau(\beta)) = \sigma(\omega^i \beta) = \sigma(\omega^i) \sigma(\beta) = \omega^i \omega^j \beta = \omega^{i+j} \beta
(\tau \sigma)(\beta) = \dots = \omega^{j+1} \beta
      So OT = TO.
```

- 3 easy observations.  $\overline{\Psi}: K \mapsto Gal(E/K)$  $E_{H} \longleftarrow 1 \; H: \Psi$ 

 $\Psi \circ \Phi = I : K \xrightarrow{E} Gal(E/K) \xrightarrow{\Psi} E_{Gal(E/K)} \overset{?}{=} K$ [Easy ? Egol(E/K) ) K | Hard ? E\_{Gal(E/K)} C K

Assume  $\alpha \in K$  and  $\sigma \in Gal(E/K)$ .  $\sigma|_{k} = I \Rightarrow \sigma(\alpha) = I(\alpha) = \alpha$ .  $\alpha \in E_{Gal(E/K)}$ .  $\Rightarrow K \subset E_{Gal(E/K)}$ 

F·ψ= I: H → EH → Gal(E/EH) = H

(Easy ⇒ H < Gal(E/EH)) Hard ⇒ H > Gal(E/EH)

Let heH

h|EH = I

4/4/07. MATTOHI WKIZ - Galois Theory. KEE ! W. LU) = O (K) Extension fields the fundamental theorem" Groups solvable groups. Extensions described by wote. (4) = (E(A) Splitting field of 3x5-15x+5 over Q -> So is not solvable. \* x+left xBek DONE solvable G: I a tower 203 = H. AH. A ... AH = G st VK He/HR-1 is abelian INEOREM: If HAG then G is solvable ( H and G/H are solvable. THEOREM: SS is not solvable. I 3 solvable > G is solvable. The many of the most 3 solvable OR OLLARY If UP is partidy in parties there there there to EIFIC 100 - DEFINITION: Let E/F be an extension. Gal (E/F) = "the galois group of E/F" = § 5: E → E | O o is an automorphism ? 7 70=00=(10 @ 01== I (+) tx e F 0x=x. - GLAIM: Gad (E/F) is a group under composition: U, T & Gal(E/F) O.T: = O.T whet of x2-t=0 th me PROOF O T . T in Gal (E/F) the one all more If x = F o(tx) = 5(x) = x. @amociativity is obvious @1:E>Ening 1 of Gal(E/F) @ If of GallE/F), then or E Gal(E/F) 14 UNIONEES - CLAIM: E=F(a.... an) /F then "o is determined by o(a,) .... o(an) (10 0, & 0, E Gal(E/F) and 5, (a, )= 0, (a,)= - = a,(an) = 0, (an).

then of = on)

```
MAPPEHAL WKIZ
                                                       PROOF
                                                       lonsider the set \{x \in E : \nabla_{i}(x) = \nabla_{i}(x)\} = K
                                                        Then OK >F
                                                                               @ K > 2 a. ... an 3
                                                    OK is a field.
                                                                                                                                                                                                                                             Extensions described
                                                                  \alpha', \beta \in K
+ \sigma_{1}(\alpha) = \sigma_{2}(\alpha)
+ \sigma_{1}(\beta) = \sigma_{2}(\beta)
                                                                                                                                                                                                                                                            21 000 mg
 5, (d) + 5, (d) + 5, (b) = 5, (d) + 0, (B) = 5, (x+B)
                                                      > x+BEK, x-BEK
                                          ' >K >E
                                      → Since KCE, then K=E.
                                           - CLAIM: If \( \sigma \) \( \text{Gal(E/K)} \) and \( \alpha \) \( \alpha \) and \( \alpha \) \( \alpha \) and \( \alpha \) \( \alpha \
                                                     COROLLARY
                                                       If of is Anity of galore, then God (E/F/ < 00
aeE, f(a) = 0 fef(x)
f(0a) = Zaibk(a) = Zb(ai)b(a)
                                                            where f = \sum a_i x^i and g \in F = \sigma(\sum a_i a_i) = \sigma(f(a)) = o/o = 0.
                                           (CAMPLE - moint constant makes makes in (3/3) has I have a hard
                                                    6=Q(15,15)/Q. J. J. J. J. (4) 31/12 3 J. 3
                                                                                             Not of x2-5=0 $55 we
                                                        x 2-3 all roots. (#13) kmb ru of I o T
                                                      \pm 13 are all roots \infty = (\infty) = (\infty) = (\infty)
                                                  o (ial (E/F) is determined by o (13) E 2 + 133. and o (15) = 2 + 153
                                                      4 choices (3/3) kan a to make
                           (a) N3 - N3 N3 N3 N3 - N3 - A (a) A) - A (a) A) - A (a) A) - A (a) A) - A (a) A (a)
```

70/4/4

sempedo n.

13 x really an automorphism?

E = .fa, + a=N3 + a=N5 + a=N3 N5 ! a= Q3 a, - 92/13 + 03/15 - 94/13/15 0= (1-00) (1+00+00) We have an explicit formula for a. Can check explicitly that a ( and b) respect + and x, hence they are really automorphism. ⇒ ETA (E/F = 21, x, B, x.B}

⇒ GA (E/F) = Zz × Zz. - DEFINITION: If H< Gal (E/F), set EH="the fixed field of H" = 2 af E: TheH, h(a) = a 3 EXTREME EATH TO HAVE MEATH MEATHER ANTONIORPHICIE. - CLAIM: EH Da field containing F

- Z X Z Z

(B) 2 (B)  $E_{(\alpha)} = Q(\sqrt{5})^{\frac{2}{2}} = Q(\sqrt{5})^{\frac{2}{5}} = Q(\sqrt{5})^{\frac{2}{5}}$   $= Q(\sqrt{5})^{\frac{2}{5}} = Q(\sqrt{5})^{\frac{2}{5}} = Q(\sqrt{5})^{\frac{2}{5}}$   $= Q(\sqrt{5})^{\frac{2}{5}} = Q(\sqrt{5})^{\frac{2}{5}} = Q(\sqrt{5})^{\frac{2}{5}}$ E = E = Q(15,15) (4) 160 > H K -> God (E/K) < God (E/F)

4 H - En onege E/En/F

```
* EXAMPLE
        E=Q(NZ, w)
                            一とすっと
       w3-1=0.
       (w2+w+1)(w-1)=0.
                                  WNI
       w2 + w + 1 = 0.
      roots = 2 w, w=3.
                                        3/2 2
       root of x3-Z
       noto= 23/2, w3/2, w2 3/2 3.
    I B X BX XB
       EXERCISE: All of these really define automorphism.
            J2 13 wodz x 002 J2
       Bd = w 10 w = 1 02
                                     So Gal(E/F) = G is not
            N2 0 N2 13 00 12
                                     commutative.
                                     161=6 => G= S3.
     - The Fundamental theorem of Galois Theory
"If charf=0 and E/F is a splitting freld, then there is a
bijective correspondence between & Intermediate extensions & and
(1-1 and onto)
                          K: E/K/F
       Esubgroups 3 **

LH < Gad (E/F) S. **
                         K \mapsto Gal(E/K) < Gal(E/F)
                      ** H -> EH of course E/EH/F
```

```
So that win wind I was in a so tel
             o. * and ** are inverses of each other
             1. Inclusion - veversing
                 H_1 < H_2 \Rightarrow E_{H_1} \Rightarrow E_{H_2}
K_1 < K_2 \Rightarrow Gal(E/K_1) \Rightarrow Gal(E/K_2)
            z. degrees/indexes/orders are respected.
[E: K] = [Gal(E/K)]
          [K:F] = [Grad (E/F): Grad (E/K)] = |Grad (E/F)|
          3. If K/F is a splitting extension, then GallE/K) A Gal (E/F)
                                                             (normal subgroup).
             Furthermore, Gal(K/F) = Gal(E/F) Gal(E/K)
     B { - Extension describable -> solvable groups.
                                        Deles De some of more poly
        0 & splitting field of
       Look (E/R) = [E: 0] = moverble by 5, no O A FORT = 25
             Consider f= 3 x5-15x + 5. (f is irreducible by Eisenstein's Criterion)
                                       f' = 15x^{4} - 15

f' = 0 \Rightarrow x^{4} = 1 \Rightarrow x = \pm 1

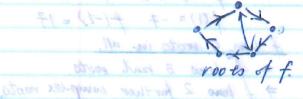
f(1) = -7 \quad f(-1) = 17
                                                  > f has 3 real roots.
appeally of the continues or to my the and or transporting
              If f(z)=0 ZEC and fERCXI then f(z)=0.
             Gal (6/R) = { i - i : I } = Z/2
             Let E be the splitting field of f. G = Gal (E/12) < permitted ion Let & ... & be the voots of F.
```

Let 5 EG. O: X being invertible must permute the nots. E = Q(d, .... x5) (3) (m) (E/K) > (m) (E/K) = 3 Oz -> Z C -> C restricts to an element of

GallE/Q) = G that keeps three not (3) I A D (M3) In E > E in place and switches the other two. (2 cycle). ( Anathopic gamen)

@ Let [Q (x,): Q] = deg f = 5 The minimal polynomial of a, is if. [Q(x):Q] = degree of min poly a Q(di) ( multiple of 5

IGAL (E/Q) = [E:Q] = divisible by 5, not divisible by 25 By Sylow, Gal(E/Q) has a subgroup of order 5. => Contains a cyclic permutation.



Let BE be the applications field of f. B = God (E/PR) < person between Let de . K to the overton of F.



Sphitting field of 3x5-15x+5

- PROPOSITION: If a subgroup a of So contains a 5-cycle and a transposition. (heeps 3 and switches other 2) then G= & PROOF

Rubik's style exercise

28/3/07. WKII MAT 401H1 - GOAL: Some polynomials cannot be "solved" using +, -, x, =, it - Galois theory a did s + bils + bins + ba (rough) GROUPS FIELDS EXTENSIONS The Fundamental Theorem of Galois are describable— "Solvable groups" (d-10 5 = 1) = (d+ 20) using "radicals" > "hard" = = dt da t = = Splitting field 3x5-15x+5 S= |S= |20. - THEOREM I THE IN IS INDIANAL IN TO PAIN IS IN MANO ( 20 MILES ) DO I - TO MILE TO - REMINDERS Id+ SH = (S) 4 FOR I d+ SA Group: x; associative but not necessarily commutative, e, inverses. H < G: H C G. closed under - and it is a group. - g/2 (R) = { A & M2x2(R): det A + O } = { (\* \*) : (\* \*) = exists} g/2(Z) < g/2(R) where g/2(Z) = {H & M22(Z) : det A +0}. - Rubike's cube group < So × Siz G, × Gz = 291,92)3 - EgJ= &gh: heH3. g. 2g- iff Fh∈H such that g=gzh. ⇒ gzg, ∈H G/H= E Cg I:g ∈ G3 |G/H| = IGI/IHI = [G:H] = the index of H in G. - PEFINITION: (NAG) N is normal in G if tye G g-'Ng = N \ Ng = gN. A HIZging INEN 3 - HD D. H D. HIZging INEN 3 ...

\* EXAMPLE

G = night d motions of the plane.  $Zf : C \rightarrow C : f(Z) = aZ + b |a| = 1, b \in C$  $f_2 \circ f_1(z) = f_2(a_1 z + b_1) = a_2(a_1 z + b_1) + b_2$ = 9,9, Z + b, 9,2 + b, 9,2 + b,2

= a(a= = - a-1b+ b)+b  $=Z-b+ab_1+b=Z+ab_1\in N$ 

 $N = \{ f(z) = |az + b \}$   $(z \mapsto az + b)^{-1} = (y \mapsto a^{-1}y - a^{-1}b).$   $(z + b_1) + b_2 = z + (b_1 + b_2),$   $(az + b) \circ (|z + b_1|) \circ (a^{-1}z \cdot a^{-1}b)$   $(az + b) \circ (|z + b_1|) \circ (a^{-1}z \cdot a^{-1}b)$   $a^{-1}y - a^{-1}b = z.$ 

- THEOREM: If N is normal in G, G/N is a group under [9,][9=]=[9,9=]

 $-f_1 = a_1 z + b_1 \qquad f_2 = a_2 z + b_2 \qquad N = \{ f(z) = 1 \times z + b \}$   $f_1 \sim f_2 \Leftrightarrow f_1 = f_2 (z \mapsto z + b)$   $= (z \longmapsto a_2(z + b) + b_2)$ (Z -> a,Z + b,) = (Z -> a,Z + a,b + b,)  $G/N = \{a: al = 13.$ 

@NAHAG and NAG then G/H = G/H/HM.

3 H<G, N G H/NAH = H-N/N

H Will A xilm of the all the last a things

- PEFINITION: G is called "solvable" if you can find a finite chain of.
subgroups 3e3=HowH, AH, AH, A. .. AH, = G such that Hx/Hx-1 is abelian (commutative).

```
* EXAMPLE
                                       (Continuentions of proof)
     G= 3 az + b 3
                                                A < 2 = . H
     Take {e3 = H. JH, = G "shortest chain"
     Normal since g-eg=e.
     But G/203 = G not abelian.
     2e3 = H. A H, = N A H2 = G
                27+63
     H_1/H_0 = N \cong (C, +) abelian.
     H_{\perp}/H_{\perp} = \frac{2}{3} a:|a|=|3| \subset (C_{\perp} \times) abelian.
            Weed to show in HIVH Host Called Co. Ith 1] - Ce.
                        H"/H" is a between so that is abusers.
   * EXAMPLE
     {('i,*)}>> {('i,*)}>> {('i,*)}>> > {('i,*)}>>> ...
   - THEOREM: Sp is not solvable if P=5.
     Sp = { 5 : {1...p3 -> {1...p3 ! 6 | exists }
     PROOF
     Suppose a chain {e3=H. AH. AH2A ... AHn-1 AHn = Sp exist such that
     Hx/Hx-1 is abelian is given.
     Let A be the subgroup of Sp generated by 3 cycles.
                (ijk).
     The smallest subgroup of Sp containing all Gik's.
   - PEFINITION: Given H < G, [H, H] = the "commutator subgroup of H"
                                 = the smallest subgroup of 6 containing all things
of the form & hinch, hill i hinge H3.
      If H is abelian, [H, H] = {e3.
   - LEMMA O: [A , A] = A (in our case) Ha
GAN OK KENK OK - ECOTE - EN E such Host K/Ky & abolio
   - LEMMA @: If H'AH" and H"/H' is abelian and H">A then H">[A, A]
```

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- (Continuation of proof)
                                                             H_n = S_p > A.

By lemma \textcircled{O}, H_{n-1} > [A, A] = A

\textcircled{O}

\textcircled
                                                             Hn-2 >[A, A] = A.
                                                                H.>A (⇒ €).
                                                                1e3 3e3
                                                                                                                                                                                                               H/H= N= (c, +) abother.
                                                   - PROOF (LEMMA @)
                                                             Let a, b & A. Need to show that aba'b' & H' (Work in H"/H').
                                                             Need to show in H"/H', that [a][b][a-][b-] = [e].
                                                              H"/H' is abelian so that is obvious.
                                                   - PROOF (LEMMA ())
                                                             a = (ijk) a = (kji) b = (kmn) b = (nmk)
                                                                   ijk kij i,j, k, m, n are different.
                                                                aba-1 b-1 = (ijk) . (kmn) . (Kji) . (umk)
                                                                                                                               me Kei enion some of Jahla
                                                                                      of A be the group it soft my pilled by is enclose
                                                                                                    =(imk)
                                                             YL, m, k, (imk) & [A, A] with a trans of h accomplian solling soll
All three cycles are in [A, A] so [A, A] A; A>[A, A].
                                  - LEIMMAD: Suppose NAG, N is solvable and G/N is solvable. Then G
                                                             is solvable
                                                            PROOF
                                                            NDHnDHndD. DHo= {e3 Hx/Hm Babelion.
                                                           G/N D Km DKm-1D. - DK = {[e]} = {N}. Such that Ku/Kx+ is abelian.
```

TI: G -> G/N

# $\Pi^{-1}(k) < G \leftarrow K < G/N$ . G > TT-1(Km)>TT-1(Km-1)> --. > TT-1(Ko) = N>Hu>Hu+> ... > Ho Verify that all the inclusions are normal Furthermore $\pi^{-1}(K_{\kappa})/\pi^{-1}(K_{\kappa-1})\cong K_{\kappa}/k_{\kappa-1}$ abelian. - LEMMA O: If NAG and G is solvable then G/N is solvable PROOF EB=H. JH, JH2 J. JHn=G Hx/Hx+1 is abelian NEW HON < HON < HON < NN=YN - CLAIM: If HK-INHX and NOG then HK-INN AHXN/N PROOF [h]=[h.h] heth neN. Take [h'] & HK-IN/N and Ch] & HXN/N [h] - [h'][h] = [h-'h'h] & Hx-1N/N. - CLAIM: Abelian is HKN/N = HKN chomomorphism HKN/N = HKN onto By first isomorphism theorem, HKN = imp = HK/HK-1 = Abelian = Abelian. HKN kerd something heHk. o(Ch]NH). = [h]HLN. verify that Opis well-defined @ p is onto.

Hilroy

HW6 returned HWZ due Math 401 Pols, Egns, Fields, March 19 2008, Week 10. on board: First two sections of "quick Reference" Discussion of front page of quit ref. Det Group: A set & with a "multiplication" (9,192) H9,92 FG st. 1. Associative 2. Fidentity (unique, Mor e) 3. Financies. H<6, G/H, 16/H/=[a:H]=16/141 "the index of NAG, NAG => G/N is a group: there

are verious
iso theorems
to be stated
late: Det H< AllE/F) => En stilled Claim En is a field. The fundamental than of Galois theory: It charF=0

and E is a splitting field our F (these exist and are unique), then there is a birections D: K/> GallE/k)
Subgroups

(K: E/K/F)
End HIV
GallE/F) ) Furthermore of & & are javerses of each other 1. inclusion polarsing. 2. degree/ index respecting [E-K]=Cal(E/K) [K:F]=[Gal(E/F]: Cal(E/K)]

Example 10 E= Q(V3, V5)/Q=F claim if set is a root of felt FEXJ, they

and perfol (EAF), then player is also
a root of f 50 13 - 13 13 - 13 Furthermore, every aut & is determined by \$103) & \$105) So G=Gal (E/F) is Zo # j lots figure out the Example 2 The splitting Field OF X3-2 over 0 E=0(\$2, W)/Q=F, with W3=1 or W744160 Det Solvable group, Eddesion by radicals.

. .

\*

n g

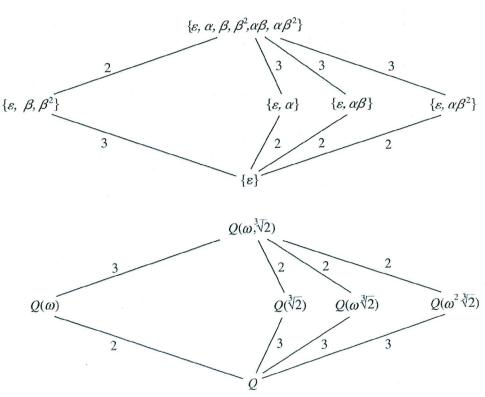
Example 5 is a bit more complicated than our previous examples. In particular, the automorphism group is non-Abelian.

**EXAMPLE 5** Direct calculations show that  $\omega = -1/2 + i\sqrt{3}/2$  satisfies the equations  $\omega^3 = 1$  and  $\omega^2 + \omega + 1 = 0$ . Now, consider the extension  $Q(\omega, \sqrt[3]{2})$  of Q. We may describe the automorphisms of  $Q(\omega, \sqrt[3]{2})$  by specifying how they act on  $\omega$  and  $\sqrt[3]{2}$ . There are six in all:

ε	$\alpha$	β	$oldsymbol{eta}^2$	αβ	$lphaeta^2$
$ \begin{array}{c} \omega \to \omega \\ \sqrt[3]{2} \to \sqrt[3]{2} \end{array} $	$ \begin{array}{c} \omega \to \omega^2 \\ \sqrt[3]{2} \to \sqrt[3]{2} \end{array} $	$ \begin{array}{c} \omega \to \omega \\ \sqrt[3]{2} \to \omega \sqrt[3]{2} \end{array} $	$ \begin{array}{c} \omega \to \omega \\ \sqrt[3]{2} \to \omega^2 \sqrt[3]{2} \end{array} $	$ \begin{array}{c} \omega \to \omega^2 \\ \sqrt[3]{2} \to \omega^2 \sqrt[3]{2} \end{array} $	$ \begin{array}{c} \omega \to \omega^2 \\ \sqrt[3]{2} \to \omega \sqrt[3]{2} \end{array} $

Since  $\alpha\beta \neq \beta\alpha$ , we know that  $Gal(Q(\omega, \sqrt[3]{2})/Q)$  is isomorphic to  $S_3$ . (See Theorem 7.2.) The lattices of subgroups and subfields are shown in Figure 32.5.

The lattices in Figure 32.5 have been arranged so that the field occupying the same position as some group is the fixed field of that group. For instance,  $Q(\omega\sqrt[3]{2})$  is the fixed field of  $\{\varepsilon, \alpha\beta\}$ .



**Figure 32.5** Lattice of subgroups of  $Gal(Q(\omega, \sqrt[3]{2})/Q)$  and lattice of subfields of  $Q(\omega, \sqrt[3]{2})$ , where  $\omega = -1/2 + i\sqrt{3}/2$ .

10 = 12 12 = WT 13 = WTZ More on split (x3-2): E=Q(32,W)=Q(K,K,K) d: Krenks B: V, Nr Leg l'extension,
So all of 53
dz: V, enson Subgroups <4, >= {e, <} <427={e,92}

# 07-401/Class Notes for April 11

From Drorbn

07-401/Navigation Panel [Show]

# **Contents**

# Today's Agenda

- Today's the deadline for the prize problem from 07-401/Homework Assignment 7!
- Reminder of the Fundamental Theorem of Galois Theory.
- Proof of the insolubility of the quintic assuming the Fundamental Theorem.
- Proofs of the easy parts of the Fundamental Theorem.
- A short discussion of the final and and the time leading to it.
- Course Evaluation Forms and a Post-Mortem discussion in the spirit of 0506-1300/Post Mortem (http://katlas.math.toronto.edu/0506-Topology/index.php?title=Post\_Mortem) and of 06-240/Classnotes For Thursday December 7.
- With luck, early dismissal!

# The Final Exam

As announced (http://www.artsci.utoronto.ca/current/undergraduate/exams/april-may-2007-exam-schedule) by the powers above, our final exam will take place on the *evening* of Tuesday April 24 between 7PM and 10PM, at New College Residence (NR) room 25.

The exam will be similar in style to the Term Test (also see On the Term Test). The material is **everything** covered in class. Everything in the test will be taken from our text book, and there will be two types of questions (or maybe sometimes the two types will be mixed within a single question):

- You may be asked to prove a theorem proven in class. The reason we prove theorems in class is that these proofs are valuable. Therefore I expect you to know them.
- You may be asked to solve exercises from the relevant chapters of the book, or minor variations thereof. These may be questions that were assigned as homework, but also, these may be questions that were not assigned before.

Office Hours. I (Dror) will hold extended office hours before the final, on Monday April 23 11AM-1PM and on the exam date, Wednesday April 24 10AM-12PM. You will be able to pick up all your graded assignments then and also on my last "normal" office hour, on Wednesday April 18 10:30AM-11:30AM. All office hours will be held at or near my office, Bahen 6178

Preparing for the Test. Read, reread and rereread everything and solve lots of exercises from the book.

My (Dror's) system when I was an undergrad was to prepare a 4-6 page 100-200 item list of points covered in class. I'd only summarize each point with one sentence, without giving any details and without trying to be precise, much like the list that I prepared for the class of February 7 (see On the Term Test). I would then go over my list again and again and again, crossing out every item for which I was sure I could complete all the details and supply all the proofs. I would only stop

when there was nothing left to cross out.

#### Good Luck!

# The Fundamental Theorem of Galois Theory

It seems we will not have time to prove the Fundamental Theorem of Galois Theory in full. Thus this note is about what we will be missing. The statement appearing here, which is a weak version of the full theorem, is taken from Gallian's book and is meant to match our discussion in class. The proof is taken from Hungerford's book, except modified to fit our notations and conventions and simplified as per our weakened requirements.

Here and everywhere below our base field F will be a field of characteristic 0.

## Statement

**Theorem.** Let E be a splitting field over F. Then there is a bijective correspondence between the set  $\{K: E/K/F\}$  of intermediate field extensions K lying between F and E and the set  $\{H: H < \operatorname{Gal}(E/F)\}$  of subgroups E of the Galois group  $\operatorname{Gal}(E/F)$  of the original extension E/F:

$$\{K: E/K/F\} \quad \leftrightarrow \quad \{H: H < \operatorname{Gal}(E/F)\} .$$

The bijection is given by mapping every intermediate extension K to the subgroup  $\mathrm{Gal}(E/K)$  of elements in  $\mathrm{Gal}(E/F)$  that preserve K,

$$\Phi: K \mapsto \operatorname{Gal}(E/K),$$

and reversely, by mapping every subgroup H of Gal(E/F) to its fixed field  $E_H$ :

$$\Psi: \quad H \mapsto E_H$$
 .

This correspondence has the following further properties:

- 1. It is inclusion-reversing: if  $H_1 \subset H_2$  then  $E_{H_1} \supset E_{H_2}$  and if  $K_1 \subset K_2$  then  $\operatorname{Gal}(E/K_1) > \operatorname{Gal}(E/K_1)$ .
- 2. It is degree/index respecting:  $[E:K] = |\operatorname{Gal}(E/K)|$  and  $[K:F] = [\operatorname{Gal}(E/F):\operatorname{Gal}(E/K)]$ .
- 3. Splitting fields correspond to normal subgroups: If K in E/K/F is the splitting field of a polynomial in F[x] then Gal(E/K) is normal in Gal(E/F) and  $Gal(E/F) \cong Gal(E/F)/Gal(E/K)$ .

## Lemmas

The two lemmas below belong to earlier chapters but we skipped them in class.

## The Primitive Element Theorem

The celebrated "Primitive Element Theorem" is just a lemma for us:

**Lemma 1.** Let a and b be algebraic elements of some extension E of F. Then there exists a single element c of E so that F(a,b)=F(c). (And so by induction, every finite extension of E is "simple", meaning, is generated by a single element, called "a primitive element" for that extension).

**Proof.** See the proof of Theorem 21.6 on page 375 of Gallian's book. □

# Splitting Fields are Good at Splitting

**Lemma 2.** (Compare with Hungerford's Theorem 10.15 on page 355). If E is a splitting field of some polynomial f over F and some irreducible polynomial  $p \in F[x]$  has a root v in E, then P splits in E.

**Proof.** Let L be a splitting field of p over E. We need to show that if w is a root of p in L, then  $w \in E$  (so all the roots of p are in E and hence p splits in E). Consider the two extensions

$$E = E(v)/F(v)$$
 and  $E(w)/F(w)$ .

The "smaller fields" F(v) and F(w) in these two extensions are isomorphic as they both arise by adding a root of the same irreducible polynomial (p) to the base field F. The "larger fields" E=E(v) and E(w) in these two extensions are both the splitting fields of the same polynomial (f) over the respective "small fields", as E/F is a splitting extension for f and we can use the sub-lemma below. Thus by the uniqueness of splitting extensions, the isomorphism between F(v) and F(w) extends to an isomorphism between E=E(v) and E(w), and in particular these two fields are isomorphic and so [E:F]=[E(v):F]=[E(w):F]. Since all the degrees involved are finite it follows from the last equality and from [E(w):F]=[E(w):E][E:F] that [E(w):E]=1 and therefore E(w)=E. Therefore  $w\in E$ .  $\square$ 

**Sub-lemma.** If E/F is a splitting extension of some polynomial  $f \in F[x]$  and z is an element of some larger extension L of E, then E(z)/F(z) is also a splitting extension of f.

**Proof.** Let  $u_1, \ldots, u_n$  be all the roots of f in E. Then they remain roots of f in E(z), and since f completely splits already in E, these are *all* the roots of f in E(z). So

$$E(z) = F(u_1, \dots, u_n)(z) = F(z)(u_1, \dots, u_n),$$

and E(z) is obtained by adding all the roots of f to F(z).  $\square$ 

# **Proof of The Fundamental Theorem**

#### The Bijection

**Proof of**  $\Psi \circ \Phi = I$ . More precisely, we need to show that if K is an intermediate field between E and F, then  $E_{\mathrm{Gal}(E/K)} = K$ . The inclusion  $E_{\mathrm{Gal}(E/K)} \supset K$  is easy, so we turn to prove the other inclusion. Let  $v \in E - K$  be an element of E which is not in K. We need to show that there is some automorphism  $\phi \in \mathrm{Gal}(E/K)$  for which  $\phi(v) \neq v$ ; if such a  $\phi$  exists it follows that  $v \notin E_{\mathrm{Gal}(E/K)}$  and this implies the other inclusion. So let P be the minimal polynomial of P over P over P if it was, we'd have that P splits in P is a splitting extension, we know that P splits in P is a contains all the roots of P. Over a field of characteristic 0 irreducible polynomials cannot have multiple roots and hence P must have at least one other root; call it P is an isomorphism P is an isomorphism P if P is a splitting field of some polynomial P over P and hence also over P is other P in the uniqueness of splitting fields, the isomorphism P is an extended to an isomorphism P is a required. P is an automorphism of P is but then P is an extended to an isomorphism P is a required. P is an extended to an isomorphism P is an extended. P is an automorphism of P is but then P is an extended to an isomorphism P is an extended. P is an automorphism of P is but then P is an extended to an isomorphism P is an extended. P is an extended to an isomorphism P is an extended. P is an extended to an isomorphism P is an extended to an automorphism of P is an extended to an isomorphism P is an extended to an automorphism of P is an extended to an extended to an isomorphism P is an extended to an automorphism of P is an extended to an extended

**Proof of**  $\Phi \circ \Psi = I$ . More precisely we need to show that if  $H < \operatorname{Gal}(E/F)$  is a subgroup of the Galois group of E over F, then  $H = \operatorname{Gal}(E/E_H)$ . The inclusion  $H < \operatorname{Gal}(E/E_H)$  is easy. Note that E is finite since we've proven previously that Galois groups of finite extensions are finite and hence  $\operatorname{Gal}(E/F)$  is finite. We will prove the following sequence of inequalities:

$$|H| \le |\operatorname{Gal}(E/E_H)| \le |E:E_H| \le |H|$$

This sequence and the finiteness of |H| imply that these quantities are all equal and since  $H < Gal(E/E_H)$  it follows that  $H = Gal(E/E_H)$  as required.

The first inequality above follows immediately from the inclusion  $H < \operatorname{Gal}(E/E_H)$ .

By the Primitive Element Theorem (Lemma 1) we know that there is some element  $u \in E$  so that  $E = E_H(u)$ . Let p be the minimal polynomial of u over  $E_H$ . Distinct elements of  $\operatorname{Gal}(E/E_H)$  map u to distinct roots of p, but p has exactly  $\deg p$  roots. Hence  $|\operatorname{Gal}(E/E_H)| \leq \deg p = [E:E_H]$ , proving the second inequality above.

Let  $\sigma_1, \dots, \sigma_n$  be an enumeration of all the elements of H, let  $u_i := \sigma_i u$  (with u as above), and let f be the polynomial

$$f = \prod_{i=1}^{n} (x - u_i).$$

Clearly,  $f \in E[x]$ . Furthermore, if  $\tau \in H$ , then left multiplication by  $\tau$  permutes the  $\sigma_i$ 's (this is always true in groups), and hence the sequence  $(\tau u_i = \tau \sigma u_i)_{i=1}^n$  is a permutation of the sequence  $(u_i)_{i=1}^n$ , hence

$$\tau f = \prod_{i=1}^{n} (x - \tau u_i) = \prod_{i=1}^{n} (x - u_i) = f,$$

and hence  $f \in E_H[x]$ . Clearly f(u) = 0, so p|f, so  $[E:E_H] = \deg p \leq \deg f = n = |H|$ , proving the third inequality above.  $\square$ 

#### The Properties

**Property 1.** If  $H_1 \subset H_2$  then  $E_{H_1} \supset E_{H_2}$  and if  $K_1 \subset K_2$  then  $\operatorname{Gal}(E/K_1) > \operatorname{Gal}(E/K_1)$ .

**Proof of Property 1.** Easy.  $\square$ 

**Property 2.**  $[E:K] = |\operatorname{Gal}(E/K)|$  and  $[K:F] = [\operatorname{Gal}(E/F) : \operatorname{Gal}(E/K)]$ .

**Proof of Property 2.** If  $K = E_H$ , then  $|\operatorname{Gal}(E/K)| = |\operatorname{Gal}(E/E_H)| = [E:E_H] = [E:K]$  as was shown within the proof of  $\Phi \circ \Psi = I$ . But every K is  $E_H$  for some H, so  $|\operatorname{Gal}(E/K)| = [E:K]$  for every K between E and F. The second equality follows from the first and from the multiplicativity of the degree/order/index in towers of extensions and in towers of groups:

$$[K:F] = \frac{[E:F]}{[E:K]} = \frac{|\operatorname{Gal}(E/F)|}{|\operatorname{Gal}(E/K)|} = [\operatorname{Gal}(E/F) : \operatorname{Gal}(E/K)]. \quad \Box$$

Property 3. If K in E/K/F is the splitting field of a polynomial in F[x] then  $\mathrm{Gal}(E/K)$  is normal in  $\mathrm{Gal}(E/F)$  and  $\mathrm{Gal}(K/F) \cong \mathrm{Gal}(E/F)/\mathrm{Gal}(E/K)$ .

**Proof of Property 3.** We will define a surjective (onto) group homomorphism  $\rho: \operatorname{Gal}(E/F) \to \operatorname{Gal}(K/F)$  whose kernel is  $\operatorname{Gal}(E/K)$ . This shows that  $\operatorname{Gal}(E/K)$  is normal in  $\operatorname{Gal}(E/F)$  (kernels of homomorphisms are always normal) and then by the first isomorphism theorem for groups, we'll have that  $\operatorname{Gal}(K/F) \cong \operatorname{Gal}(E/F)/\operatorname{Gal}(E/K)$ .

Let  $\sigma$  be in  $\mathrm{Gal}(E/F)$  and let u be an element of K. Let p be the minimal polynomial of u in F[x]. Since K is a

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HW10(hst) on web by noon to morrow.

Math 401 Pols, Egns, Fields, April 42007, Week 12. Galois Theory Fields Fund The Trans Solvable a: extensions to scribable by roots > Solvable 20 QCY=HO NH, NH2 N- NH=G St. @HK/HK-1 ASKS9 box/1.0 Solition \_\_\_ not solvable XIF HYG Then GSOWALD IFF H&G/H AR. 3 X5-15 X+5 X SS is not solvable Def E/F => Gal(E/F) claim it is a group then o(a) is a root too, Jaim JEGal(Fla, an)/F) is Letermined by Example 1 F = Q(V3, V5)/Q=F So Gal(E/F) V3 -> V3 -V3 V3 -V3 =12×12 V5 -> V5 V5 -V5 I & B &B DEF The Fixed Cicle of HKSal(E/F) Claim It is a First. continue vample 1 Exp = Q(V5) Exp = Q(V3) EXIBY = 0 EXT = 0 (13, 15) Thus Figure 32.4  $E < \alpha \beta 7 = Q(V15)$   $E \times ample 2 : E = Q(W = e^{extis} = \frac{1}{2} + \frac{1}{2}, \frac{1}{3} = \frac{1}{2} + \frac{1}{2}, \frac{1}{2} = \frac{1}{2} + \frac{1}{2}, \frac{1}{2} = \frac{1}{2} + \frac{1}{2} = \frac{1}{2}$ 

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\* HW9 on web by noon Math 401 Pols, Egns, Fields, March 28 2007, Week 1/
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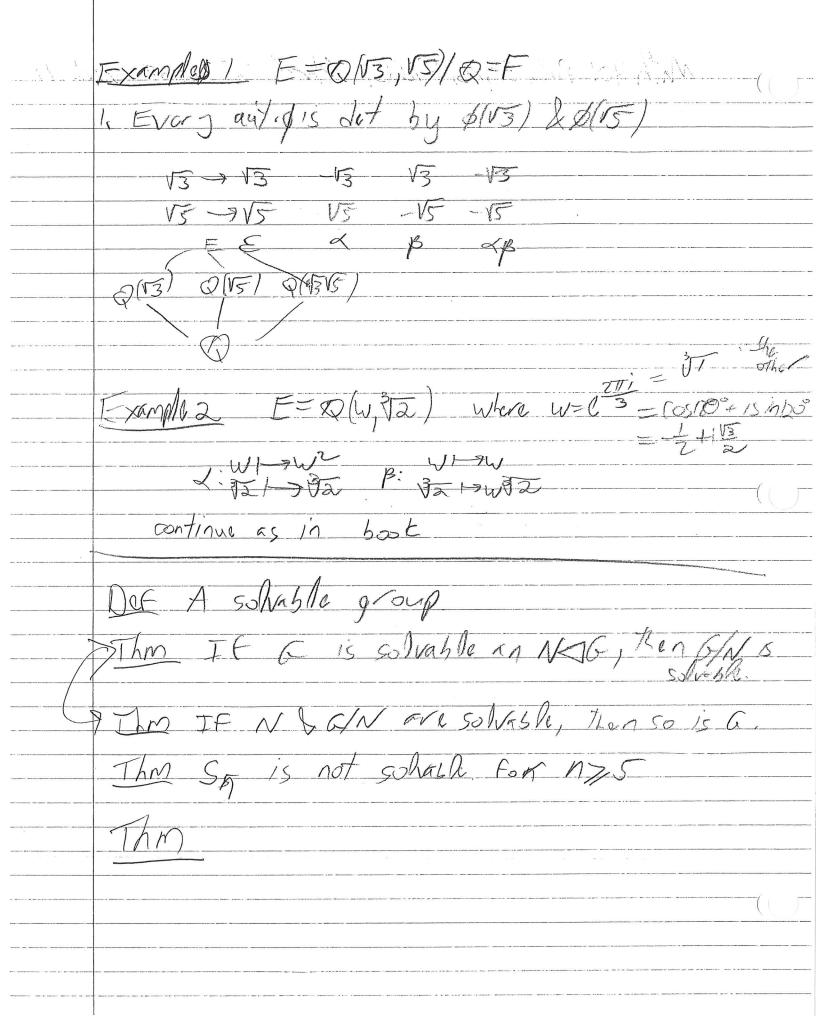
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HW7 on Web by noon tommorow.

North 401 Pols, Egrs, Fields, March 142007, Week 9 Last west's key theme: "Extending a Field. I Today's agarda (Passive)1, E/F, Q. an EF, F(a1, a2.) - F(a2, a, 1/a3, ) 1. Review of Ast for Existence & uniqueness are obvious. 2. Adding a single root: p imdudble in FGT Uniquents Always Q: F- 7 150, 6(P)=p' P(N=0, P(N)=0 reative. -) F(a)=F(a) 3. Splitting a polynomia QF=a(x-a,). (x-a,) in E& F minimal y/ prospay Theorem FEFED his a multiple zero in some extension Ciff flaf have a common factor of dig?

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(cg) - f'+g' 5. f'=0 =) f=C 1.

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E/F Finite => E/F algebraic.

a is algebraic OVV F => F(a)/F 15 Finite Octinition Theorem IF K/E/F, then [K:F]=[K:E][E:F] Proof of goal Discussion of the just for fan exercise 37 - 1 15/3 V2 + 47

HW7 on webb of by noon to morred

Math 401 Pols Eggs Fields, March 12 2008, West 9.

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2. Geometric constructions.

3. Obs kends from days b. a. algorithms Sayxis

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aDef [E:F] the dimension of E as pa V.s. oper F.

Say Bat E/F is finite if E:F) is Figit. They a is als over F = Flatt is Finite. Thm If E/E/F then CK:FJ=[R:F][E:F] Proof of goal 1 France SQL 3, 37 J. QJ=Q. a compass (siver a Unit intered) Odds & ends as on March 21, 2007 cannot costruct cos 20°.

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Goal: I If A, b (E are dg., so are annihilas form) 2. Geometric constrations

aff, a-6, ab, a/6 (Ng numbers form) 2. Geometric constrations

2. a; Ng, b solve 5a, x'-0 = b is aff. chapter 2. [Ag nums are algorished] 4. Start of calois the oft. [E:F] := Jim of F as a Vis over F. This a rug over F = FAI/F is Finite. Thm If K/E/F, then [k:F]=[k:E][E:F] Proof of goal. Geom const. using a rader len compress. Given a unit interest, cannot construct 3/2 given an angle cannot construct % IT is transcardantal (not algebraic) -> cannot square a cinte odde and ends E/F, acE Fal is a simple extension. Thm a alg =)  $F(\alpha) = F(x)/p$ where p is the (unique) minimal polymonic p(x) = p(x)/p =DOF The Minimal poly claim of exists and is unique, Claim It P is minpoly(a), and Ela) =0, Then plf Example [Q(V2, V3): Q]=12 Example Find the min ply of V3+VF OVER 10 10 /OVER

<u>C.</u>	Thm If Char F= 0 Xx,BEE/F, Then	(()
	If $SEE$ st. $F(x,\beta) = F(8)$ . element & (so by induction, Finite Ag extensions are	
	start of Galois:  Gal (E/F) IS a group  H<6 (D) => EHD IS E/EH/F  "The Fixed Field of H".	

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Math 401 Pols Egns Fields, March 5 2008, week 8 \* Discussion of TT \* HW6 on Web by non tomorrow.

\* Some philosophy:

Def A field whaten & A symmetry of F/F

"an automorphism of F/F

Well talk about two vays of extending fields:

later > 1. By adding ta, va, it. Pess symmetry

to by - D. By throwing in all roots of highly grander;

"splitting fields
exists and are cryptly unique". Thro (Kronecker) Let FEF [X] be non-constant. Then

J E/F in Which F has a root 0 Examples 2+1/18, X5+2X+2=(X24)(X3+2X+2)/2/3. Duf PEFES splits in E/F; A splitting field Exf.

Example 2-2 over & konr/R. over F

This is a specific to the splitting field Exf.

Duf (E)/Fig. (ag. agEE), F(ag. ag) Example = "The smallest subfield of "=" The intersection =

Example = "Everything the that can
be reached from Fugg, any by do operations" claim If FFEDSplits in E, arreits roots in Examples  $X^{4}-X^{2}-Z=(X^{2}-Z)(X^{2}+1)$  over  $X^{2}+X+2$  over Z/3.

08-40) week 8, continued. Then Let FFFEX). A splitting field for F operF Ihm Let PEFEN be ind if aCE/F & Paj=0 Then F(a) = F[x]/p> Via g: F[x]/p> > F(a)

S.t. p(x) = a. Furthermore, if deg p=n, then every etement of F/a) can be written G+G9+C292+...+Cn1911 With all CIEF, in a anique way, corollary If PEFEN is irred, a EF/F and LEE/F
are roots of P, than F/a) = F(6). Thm Any two splitting fields of fifting over to are isomorphic and isomorphic and isomorphic field of fifting field of field of fifting field of fie emma PEFEXD IMON, Ø:F->F' 150, oxt of F, a a root of F' ig somext. of F/ thin Jy: F(a) -> F(a) 150, S.t. 4/F = p.

# Template:08-401/Results of the Term Test

### From Drorbn

The Results [print]

A total of 27 students took the exam; before appeals the average grade is 64.66 and the standard deviation is 18.79.

The full list of grades is: (31 43 43 46 47 49 50 52 53 54 55 60 60 61 61 62 65 73 75 76 82 83 92 99 99 100).

The results are quite similar to what I expected them to be, perhaps a bit on the low side.

Individual grades are on CCNet (http://ccnet.utoronto.ca/20081/mat401h1s/) .

## How should you read your grade?

■ If you got 100 you should pat yourself on your shoulder and feel good.

■ If you got something like 95, you're doing great. You made a few relatively minor mistakes; find out what they are and try to avoid them next time.

■ If you got something like 75 you're doing fine but you did miss something significant, probably more than just a minor thing. Figure out what it was and make a plan to fix the problem for next time.

- If you got something like 55 you should be concerned. You are still in position to improve greatly and get an excellent grade at the end, but what you missed is quite significant and you are at the risk of finding yourself far behind. You must analyze what happened perhaps it was a minor mishap, but more likely you misunderstood something major or something major is missing in your background. Find out what it is and try to come up with a realistic strategy to overcome the difficulty!
- If you got something like 35, most likely you are not gaining much from this class and you should consider dropping it, unless you are convinced that you fully understand the cause of your difficulty (you were very sick, you really couldn't study at all for the two weeks before the exam because of some unusual circumstances, something like that) and you feel confident you have a fix for next time. The deadline for dropping a class this semester is soon: Sunday March 9.

### Appeals.

Remember! Grading is a difficult process and mistakes always happen - solutions get misread, parts are forgotten, grades are not added up correctly. You must read your exam and make sure that you understand how it was graded. If you disagree with anything, don't hesitate to complain! Dror graded everything, so appeals should go directly to him.

The deadline to start the appeal process is Wednesday March 19 at class time.

#### Retrieved from

■ This page was last modified 14:08, 2 March 2008.

HW6 on Web by noon tomorrow.

## 07-401/Class Notes for March 7

### From Drorbn

### **Contents**

- 1 Class Plan
  - 1.1 Extension Fields
  - 1.2 Splitting Fields
  - 1.3 Zeros of Irreducible Polynomials

### Class Plan

Some discussion of the term test and HW6.

Some discussion of our general plan.

### **Extension Fields**

**Definition.** An extension field E of F.

**Theorem.** For every non-constant polynomial f in F[x] there is an extension E of F in which f has a zero.

Example  $x^2 + 1$  over  $\mathbb{R}$ .

**Example** 
$$x^5 + 2x^2 + 2x + 2 = (x^2 + 1)(x^3 + 2x + 2)$$
 over  $\mathbb{Z}/3$ .

**Definition.**  $F(a_1,\ldots,a_n)$ .

**Theorem.** If a is a root of an irreducible polynomial  $p \in F[x]$ , within some extension field E of F, then  $F(a) \cong F[x]/\langle p \rangle$ , and  $\{1, a, a^2, \dots, a^{n-1}\}$  (here  $n = \deg p$ ) is a basis for F(a) over F.

**Corollary.** In this case, F(a) depends only on p.

### **Splitting Fields**

**Definition.**  $f \in F[x]$  splits in E/F, a splitting field for f over F.

Theorem. A splitting field always exists.

**Example.** 
$$x^4 - x^2 - 2 = (x^2 - 2)(x^2 + 1)$$
 over  $\mathbb{Q} \cdot \mathbb{Q}$ 

07-401/Navigation Panel [Hide]

# .	Week of	Links
1	Jan 10	About, Notes, HW
2	Jan 17	HW2, Notes
3	Jan 24	HW3, Photo, Notes
4	Jan 31	HW4, Notes
5	Feb 7	HW5, Notes
6	Feb 14	On TT, Notes
R	Feb 21	Reading week
7	Feb 28	Term Test
8	Mar 7	HW6, Notes
9	Mar 14	HW7
10	Mar 21	HW8
11	Mar 28	HW9
12	Apr 4	HW10
13	Apr 11	
S	Apr 16-20	Study Period
F	Apr 24	Final

Add your name / see who's in!

Register of Good Deeds

**Example.** Factor  $x^2 + x + 2 \in \mathbb{Z}_3[x]$  within its splitting field  $\mathbb{Z}_3[x]/\langle x^2 + x + 2 \rangle$ . (\*\*\*)

**Theorem.** Any two splitting fields for  $f \in F[x]$  over F are isomorphic.

Lemma 1. If  $p \in F[x]$  irreducible over  $F, \phi : F \to F'$  an isomorphism, a a root of p (in some E/F), a' a

Lemna 2

root of  $\phi(p)$  in some E'/F', then  $F(a) \cong F'(a')$ .

Lemma 2. Isomorphisms can be extended to splitting fields.

## Zeros of Irreducible Polynomials

Definition. The derivative of a polynomial.

Claim. The derivative operation is linear and satisfies Leibnitz's law.

**Theorem.**  $f \in F[x]$  has a multiple zero in some extension field of F iff f and f' have a common factor of positive degree.

Lemma. The property of "being relatively prime" is preserved under extensions.

**Theorem.** Let  $f \in F[x]$  be irreducible. If  $\operatorname{char} F = 0$ , then f has no multiple zeros in any extension of F. If  $\operatorname{char} F = p > 0$ , then f has multiple zeros (in some extension) iff it is of the form  $g(x^p)$  for some  $g \in F[x]$ .

Definition. A perfect field. (Char o of FI=F.)

Theorem. A finite field is perfect.

Theorem. An irreducible polynomial over a perfect field has no multiple zeros (in any extension).

**Theorem.** Let  $f \in F[x]$  be irreducible and let E be the splitting field of f over F. Then in E all zeros of f have the same multiplicity.

Corollary. f as above must have the form  $a(x-a_1)^n\cdots(x-a_k)^n$  for some  $a\in F$  and  $a_1,\ldots,a_k\in E$ .

**Example.**  $x^2 - t \in \mathbb{Z}_2(t)[x]$  is irreducible and has a single zero of multiplicity 2 within its splitting field over  $\mathbb{Z}_2(t)[x]$ .

Retrieved from "http://katlas.math,toronto.edu/drorbn/index.php?title=07-401/Class Notes for March 7"

■ This page was last modified 17:41, 7 March 2007.

## 08-401/On the Term Test

### From Drorbn

Our Term Test will take place on February 27 at 6:20PM at Galbraith (GB) 304 on 35 St. 08-401/Navigation Panel [Hide] George Street, across from the Bahen Centre for Information Technology. It will be two hours long.

# Week of... Links

1 Jan 9 About, Notes, HW1

The material is **everything** covered in class until and including the class of February 13, 2007. Everything in the test be taken from our text book, and there will be two types of questions (or maybe sometimes the two types will be mixed within a single question):

- You may be asked to prove a theorem proven in class. The reason we prove theorems in class is that these proofs are **important**. Therefore I expect you to know them.
- You may be asked to solve exercises from the relevant chapters of the book, or minor variations thereof. These may be questions that were assigned as homework, but also, these may be questions that were not assigned before.

Office Hours. Dror will hold extended office hours on the week of the Term Test, on Monday from 2PM to 4PM, on Tuesday at the usual time (12:30-1:30) and on Wednesday from 1:30PM to 3PM, all at or near Bahen 6178. Yichao Zhang will hold his usual office hours, on Tuesday 1:00-3:00 at the Math Aid Centre, Sidney Smith 1071.

**Preparing for the Test.** Read, reread and rereread everything and solve lots of exercises from the book.

My (Dror's) system when I was an undergrad was to prepare a 2-3 page 50-100 item list of points covered in class. I'd only summarize each point with one sentence, without giving any

details and without trying to be precise, much like the list below that I prepared for the class of February 6. I would then go over my list again and again, crossing out every item for which I was sure I could complete all the details and supply all the proofs. I would only stop when there was nothing left to cross out.

#	Week of	Links					
1	Jan 9 About, Notes, HW1						
2	Jan 16	HW2, Notes					
3	Jan 23	HW3, Photo, Notes					
4	Jan 30 HW4, Notes						
5	Feb 6 HW5, Notes						
6	Feb 13	On TT, Notes					
R	Feb 20	Reading week					
7	Feb 27	Term Test					
8	Mar 5 HW6, Notes						
9	Mar 12 HW7, Notes						
10	Mar 19	HW8, Notes					
11	Mar 26 HW9, Notes						
12	Apr 2 HW10, Notes						
13	Apr 9 Notes						
S	Apr 14-18 Study Period						
F		Final					
	Add your name / see who's in!						
	Register	of Good Deeds					

#### **Good Luck!**

### Summary of the class of February 7:

- A long division computation.
- f(a) is the remainder of the division of f(x) by x a.
- a is a zero of f(x) iff x a is a factor of f(x).
- The multiplicity of a zero.
- lacksquare A polynomial of degree n has at most n roots, counting multiplicities.
- The roots of  $x^2 + 3x + 2$  in  $\mathbb{Z}/6$ .
- The roots of  $x^n 1$ .
- **Definition.** A Principle Ideal Domain (PID).
- F[x] is a PID and a criterion for  $I = \langle q(x) \rangle$ .

- **Example.** the complex numbers and  $\mathbb{R}[x]/\langle x^2+1\rangle$ .
- **Definition.** Units in a ring.
- **Definition.** Reducible and irreducible polynomials.
- Reducibility in degrees 2 and 3.
- Primitive polynomials.
- The product of primitive polynomials is primitive.
- The content of a polynomial.
- The content of a product is the product of the contents.
- If  $f \in \mathbb{Z}[x]$  is reducible in  $\mathbb{Q}[x]$ , it is reducible already in  $\mathbb{Z}[x]$ .

Retrieved from "http://katlas.math.toronto.edu/drorbn/index.php?title=08-401/On\_the\_Term\_Test"

■ This page was last modified 18:14, 13 February 2008.

No Credit For "trying"

Solve 5 of the following 6 problems. Each of the problems is worth 20 points. You have two hours. Neatness counts! Language counts!

**Problem 1.** Consider the ring  $\{0, 2, 4, 6, 8\}$  under addition and multiplication modulo 10. Does it have a unity?

Tip. This, of course, is not just a yes/no question. You are expected to fully justify your answer, whatever Musty 15 6 it is.

### Problem 2.

5 1. Define "an integral domain".

Ç 2. Define "a field".

3. Prove: A finite integral domain is a field. -By not clear where domain ness was

Tip. As always in math exams, when proving a theorem you may freely assume anything that preceded it but you may not assume anything that followed it.

 $\rightarrow$  Problem 3. Let R be a commutative ring with unity and let A be an ideal in R. Prove that R/A is a field if and only if A is maximal.

Tip. Don't forget! There are two directions to prove here!

**Problem 4.** Find all ring homomorphisms from  $\mathbb{Z}/6$  to  $\mathbb{Z}/10$ . Tip. Here, of course, you have to explain both why the homomorphisms you found really are homomor-- 8 disnot chack well-definitioner phisms and why there are no more.

### Problem 5.

1. Let F be a field, let f be a polynomial in F[x], and let a and b be two different elements of F. Prove that the remainder for the division of f by (x-a)(x-b) is

$$\frac{f(b) - f(a)}{b - a}(x - a) + f(a).$$

2. Compute the remainder for the division exercise  $\frac{x^{2008}}{x^2-1}$ , done in  $\mathbb{Q}[x]$ .

**Problem 6.** Prove that the polynomial  $f = 3x^5 + 15x^4 - 20x^3 + 10x + 20$  is irreducible over Q. If you are using any major theorem, you need to quote it in full, but you don't need to prove it.

### Good Luck!

## Do not turn this page until instructed.

## Math 401 Polynomial Equations and Fields

## Term Test

University of Toronto, February 27, 2008

Solve 5 of the 6 problems on the other side of this page.

Each of the problems is worth 20 points. You have two hours to write this test.

#### Notes.

- No outside material other than stationary and a basic calculator is allowed.
- The final exam date was posted by the faculty it will take place on the *evening* of Tuesday April 28 between 7PM and 10PM, at BN2S (Large Gymnasium, South End, Benson Building, 320 Huron Street (south of Harbord Street), Second Floor).
- Neatness counts! Language counts! The *ideal* written solution to a problem looks like a proof from the textbook; neat and clean and made of complete and grammatical sentences. Definitely phrases like "there exists" or "for every" cannot be skipped. Lectures are mostly made of spoken words, and so the blackboard part of proofs given during lectures often omits or shortens key phrases. The ideal written solution to a problem does not do that.
- New! You will get 20% of the credit for any problem for which you will write explicitly "I don't know how to solve this problem" (whole problems only!).

### Good Luck!

Math 401 Pols, Egns, Fields, Feb 14 2007, Week 6 \* APUS Tody: 1. Why care about irreductible poly?

\* TT (at GB/20) \* related to Fields.

\* TT (at GB/20) \* relatives of primes (fungame).

\* Last (fic. 2, criteria for irreductibility Theorem Let PAFFEX). The SP(x) 7 is maximal IFE P is in reducible OF P maximal => If reducible, contradiction piroducible => CICFEJ, FEDA PID => I=(9/5))

if pisirred,

or FDJKP(A) is a field. COC P, a, b FF[x], P yrd, P/a.b => P/a or P/b. Examply 1. 25 (3+x+1) is a field w/ 8 demonts. 2. Z3[X] <x+17 is a field of 9 christs Theorem Let FEZGE) be non-zero le non-unit. Then (i.e., princs) irred of deg 71) & This is unique up to apermutation & up to signs. Example The sichermon dice 1223346 131568 @ and Their uniquess DE an irad factor of (X+x5+x+x5+x2+x)=x4x+1)2x2+x+1)2 is of the form X (x+1) (x2+x+1) (x2-x+1) 4 where 059, 1, 1, 452. P=Xa1+Xa2+ +Xa6 t. Evaluate P(1) 2. evaluat P(0). - Cont.

40/ Week 6 Page 2. Theorem F red mod P OF F, deg E=degfj If F 15 11/ed then F is irred. Example 21×3-3×2+2×+9 1. Irred over That 2. ITTEL OVAL 1/3 but antuse They. Example 21×3-3×2+2×+8 1. VCS OFC 7/2 2,11/13 OW/ 2/5 Eisenstein's Criturion: anxn+...+a.

Plan, 1 Man. Plan, p2fa. =) I/RJ OVEC 7/10 COC X-1 = X-1, +1 +5 100ed.

(X2+1/2+1) = X1/4

Today's 1907da: Reducible pollys: Math 401 Pols egn's Fields, Feb 6 2008, week 5. F=9.h irreducible polys The IFF is a field and F,gEF[X], g to => - the MSt. (math is a doct IN 9, rEF [x] s.t. F=99+1 & degr = deg 9 of: "The quotient for F/9".

The remainder for F/9". Example  $\frac{26}{97} = 40275$   $\frac{27}{97} = 40275$   $\frac{27$ Example F=x5-2 9= x2-x-1 XY + X3 X4 - X3 - X2 9 = x3+x2+2x+3  $2x^3 + x^2$  $2x^3 - 2x^2 - 2x$ r= 5×+5. 0 3x-2x-2 3×2 -3× -3 CON  $F \in F[X] = 7 \cap F[A]$  is the remainder for  $f(X)/X - \alpha$ .

CON  $F(A) = 0 \iff (X-\alpha)/F$ The matter of  $f(X)/X - \alpha$ . cor in F[x] a poly of day n has at most n zeros,

Counting with multiplicity. (Example x3,x2-x1) = = (x4)x(x1-x1) = = (x4)x(x1-x1) = (x2+3x+2 has

4 zeros in 2/6. O DOF PID Thm FEXT is a PID; IF A is an ideal, it is gorciated by Example FI-OF(i) in 18ExJ any non-zero ply ifat of minden

Cont: Det ont anit. Det unit in R Det F is irred in DEX IF F=9h => gor by is a unit. otherwise f is reducish Hyample 2×2+4 is irred other to ved over Z 1/10 J ofor IR Ved ofor C. XT+1 irred over Z/3 ved over Z/5. Thm FEFEX, dog E=2,3 => Fis Was IFF 17 has Then FEREN if it is reducible Afer QUO, it is also reducible over ZEN.

(hence the contra-positive). Example (x2+x-2=(3x-3/2)(2x+4/3) Def primitin poly  $\in \mathbb{Z}[S]$  Then primitives is primitive. Well  $\int_{S} \mathbb{Z}[S] = \mathbb{Z}[S]$  Then primitive. It is well defined.

Then C(Fg) = C(F)C(g). PF  $\Rightarrow$  f  $\Rightarrow$  f

	7/2/06
0-	COROLLARY: (Remainder theorem) If F is a field and flex = Flex I. Then flax is the
T.	remainder in the dission of too by
	PROOF SUPERIOR AND ADDRESS OF THE PROOF ADDRESS OF THE PROOF AND ADDRESS OF THE PROOF ADD
	f(x) = g(x)g(x) + v(x),  deg(x) < deg(g). Let $g(x) = x - a$ . $f(x) = (x - a)g(x) + v(x).$
	Let g(x) = x-a.
	f(x) = (x-a)g(x) + y(x).
	The state of the s
	Since degree of x-a is 1, deg(g) > deg(r) so deg(r) = 0.
	V(x) = b a winstant.
	1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 -
	Let x=a
	$f(a) = (a-a)g(a) + \kappa(a)$
	f(a) = v(a)
	The RO of MO P A part of Early Carry Carry
(E) -	- COROLLARY: If F is a field and fox) & FIXI, then a is a zero of fix) iff x-a is a
	factor of fa).
	Fig. Mark said Syn St. B. S.
3.	- COROLLARY : Polynomials of degree u have at most u zeros.
4	f(x)=0 has at most n zeros counting multiplicity. for effect fin a field.
	1700 017
- L	the industion on degree of for).
~	
	If $y=1$ $f(x)=ax+b$ $a\neq 0 \Rightarrow x=-\frac{b}{a}$ .
	Use induction on degree of $f(x)$ .  If $n=1$ , $f(x)=ax+b$ $a+o \Rightarrow x=-\frac{b}{a}$ .  If he are polynomial $f(x)$ with $deg(cx)=k$ , $g(x)$ has at most $k$ zeros.
	If for any polynomial g(x) with defloy)= K, g(x) was at most we correst
	If for any polynomial g(x) with defloy)= K, g(x) was at most we correst
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	If for any polynomial got with neglog)= K, got has at most we cores.  For n=k+1, f(x) with deg f = K+1  O f(x) has no zero TRUE  O f(x) has some zeros.
	If for any polynomial got with neglecy)= K, got has at most we correct  For n=k+1, f(x) with deg f = K+1  O f(x) has no zero TRUE  O f(x) has some zeros.
	If for any polynomial $g(x)$ with deg $f = K + 1$ For $n = k + 1$ , $f(x)$ with deg $f = K + 1$ O $f(x)$ has no zero TRUE  O $f(x)$ has some zeros.  Choose any zero $\alpha$ of $f(x)$ $f(x) = (x - \alpha) h(x)$ for some $h(x) \in F(x)$ .
	If for any polynomial $g(x)$ with $deg f = K + 1$ For $n = k + 1$ , $f(x)$ with $deg f = K + 1$ O $f(x)$ has no zero TRUE  O $f(x)$ has some zeros.  Choose any zero $\alpha$ of $f(x)$ $f(x) = (x - \alpha) h(x)$ for some $h(x) \in F(x)$ .
	If for any polynomial $g(x)$ with $deg f = K + 1$ For $n = k + 1$ , $f(x)$ with $deg f = K + 1$ O $f(x)$ has no zero TRUE  O $f(x)$ has some zeros.  Choose any zero a of $f(x)$ $f(x) = (x - a) h(x)$ for some $h(x) \in F(x]$ .  Figure $f(x) = x - a$ we know hix) has at most $k$ zeros.
	If for any polynomial $g(x)$ with $deg f = K + 1$ For $n = k + 1$ , $f(x)$ with $deg f = K + 1$ O $f(x)$ has no zero TRUE  O $f(x)$ has some zeros.  Choose any zero a of $f(x)$ $f(x) = (x - a) h(x)$ for some $h(x) \in F(x)$ . $\Rightarrow deg h = k$ .  By corrollary $\textcircled{O}$ we know hix) has at most $k$ zeros. $\Rightarrow f(x)$ has at most $k + 1$ zeros.
×>	If for any polynomial $g(x)$ with $deg f = K + 1$ For $n = k + 1$ , $f(x)$ with $deg f = K + 1$ O $f(x)$ has no zero TRUE  O $f(x)$ has some zeros.  Choose any zero a of $f(x)$ $f(x) = (x - a) h(x)$ for some $h(x) \in F(x]$ .  Figure $f(x) = x - a$ we know hix) has at most $k$ zeros.

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	hao 4 zero.	1
	3023	
	* EXAMPLE = 1/2 / h. (e) h. (e) . (p) galo> (s)mily 1 . (x)m1 xxx (xop = (v))	
	The complex zeros of x"-1 & CTX]. Find all zeros of x"-1 over a.	
	DE Moivre's Theorem: (1050 + isin 0) K = cosk @ + isinke KEZ.	
	$X_{i} = \cos(\frac{2\pi}{n}) + i\sin(\frac{2\pi}{n})$ is a zero of $x'' - 1$	
	The state of the s	
	$X_n'' = (\cos \frac{\pi}{n} + i\sin \frac{2\pi}{n})^n = \log n \times \frac{2\pi}{n} + i\sin n \times \frac{2\pi}{n} = 1$	
	=> x"- 1=0	
	6-8 131	
	$x_k = x_1^k = \cos \frac{k^2 \pi}{n} + i \sin \frac{k^2 \pi}{n}  k = 0, 1, 2, \dots, m-1$	
	$ x  = x_1^{\kappa} = \cos \frac{\kappa^2 \pi}{n} + i \sin \frac{\kappa^2 \pi}{n}  k = 0, 1, 2, \dots, \kappa = 1.$ $ x  = i + x_1^{\kappa} = \cos \frac{\kappa^2 \pi}{n} + i \sin \frac{\kappa^2 \pi}{n}  k = 0, 1, 2, \dots, \kappa = 1.$ $ x  = i + x_1^{\kappa} = \cos \frac{\kappa^2 \pi}{n} + i \sin \frac{\kappa^2 \pi}{n}  k = 0, 1, 2, \dots, \kappa = 1.$	
5 H p	On Coccurry : If I am held and for a FOG. There is is a core of for if x	
	- DEPINITION: Principal Ideal Domain (PID) is an integral domain & in	
	which every ideal has the form (a) = Evalver & for some ack.	
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a kjeld	A DED a PID . I whather process so we so the sea of the	
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	- THEOREM: If F is a field, FTXI is a PID SOME AND A STATE OF THE PROOF	
, >	Assume that I is an ideal of FEXI.	
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	© $I \neq 203$ assume that $260 \in I$ at deg( $960$ ) in the smallest Vf( $x$ ) $\in I$	
	CLAIM: / = (g(x))	
	At(x) & T	
	T(x) - y(x) T(x) for some g, v et(x) deg v(x) < deg o(x)	
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	= + f(s) lims at mate n+1 zeros. 0 = (x) v €	
- AAA	$f(x) = g(x) \cdot g(x)$ , $\forall f(x) \in \langle g(x) \rangle \leq \Gamma  \forall \tau = \langle g \rangle$ .	
horall	Vf(x) & <g(x)> \le I \ Z \ T = <g>. SUMMARS W</g></g(x)>	
	$I \leq \langle g(x) \rangle$	

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B I +0, o(x)+0 € I and deg(g(x)) =0 > g(x)= a +0.
                     > I=F (x)=<1>.
            * EXAMPLE
                    p: R[X] → & where f(x) $ f(x) f(x) ∈ R[X], f(a) ∈ C.
                    ker $ = \(\frac{1}{2}g(x)\) \(\text{R[X]} \) \(\phi(g(x)) = g(\ti) = 0\)
                     x2+1 & ker 4. since i2+1=0.
                     Ker$ = (x2+1).
                   know that Rher & = 1m %.
                    MXJ/(x2+1>= Im = C.
               - DEFINITION: R is an integral domain, fox) ER[x], fox) to or a unit in Rty.
for is called irreducible if whenever fix)=g(x) in(x), g(x), u(x) ER[x]
                     then g(x) or h(x) is a unit in RTXI.
                     If f(x) is not irreducible, f(x) is called reducible f(x) +0, f(x) is not a unit
               - NOTE: If R= F a field, fox) is irreducible (=> fox) cannot be written as
                      g(x) h(x) with deg(g) (deg(f), deg(h) (deg(f).
               * EXAMPLE
                      f(x)=2x2+4.
                     OR = Q f(x) is irreducible.
                     OR = Z fox) is reducible.
                      f(x) = 2 \times (x^2 + 2)
                     MARKET STORY OF MOX . SEE SHOWING THE SHOWING A PROPERTY OF THE SHOWING THE SH
                     @ R=IR, & f(x) is irreducible.
                  * EXAMPLE
                       f(x) = x2-2.
                       OR - Q f(x) is irreducible.
                      OR = IR f(x) is reducible.
                       f(x) = (x^2 - 2) = (x - \sqrt{2})(x + \sqrt{2}).
```

	f(x)=x²+1. 3 + x=(x)p = 0 = (xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
	OR=R fox) is irreducible.  OR=C f(x) is reducible
	@ R = c f(x) is reducible
	$\phi(x) = (x + \sqrt{1})(x - \sqrt{-1})$
	(3) R = Z3 = {0,1,23. f(x) in inveducible.
	$ \Psi P = 1/- + f(x)$ in reducit to
	$ \mathcal{D}R = \mathbb{F}_p = \mathbb{Z}_p  \text{p is prime.}  f(x) \text{ is sirveducible if } p \equiv 3 \mod 4 $ $ \text{I veducible if } p \equiv 1 \mod 4 $
	Lreducible if p = 1 mody
	A MALE & SANCES OF MARKET
_	THEOREM: (Reducibility Test for degree 2 and 3) Let F be a field. If fix) & FIXI  deg(f) = 2 or 3, then f(x) is reducible iff f(x) has a zero over F.
	deg(f)=2 or 3, then f(x) is reducible iff f(x) has a zero over F.
1 My 20 31	Mr. on a resident transport of the state of
DIA	f(x) is reducible = f(x) = g(x) h(x) with deg (g), deg(h) < deg (f), g(x), h(x) & F[x]
	deg(f) = deg(g) + deg(h)
19 10° 4 100	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$
	> 1f deg(g)=1, g(κ)=ax+b > x=- \( \frac{1}{6} \) € F.
12 :15	- \( \tau \) \( \tau \
	= - a is a zero of fox) since f(x)=g(x).h(x).
	AL AL PER
*	EXAMPLE
	fon=x4+22+=(x2+1)2 is reducible over 18.
	but f(x) has no zeros over IR.
	> Theorem is not true for deg(f) > 3.
	(2+, N) = 2 = (M)
_	DEFINITION & The content of a nonzero polynomial for=aux"+ tax+a over Etx]  Kapal(anana, a.) a; EZ. i=0,1,2,
	$K \circ col(a_n a_{n-1}, a_i a_i)$ $a_i \in \mathbb{Z}$ . $i = 0, 1, 2,$
-	CAME I TO THE THE PARTY OF THE
-	PEPINITION: A primitive polynomial is an element in ZTXI with content 1.
	for x 22
*	EXAMPLE SAMONES (1) (1) (1) (1)
	$2x^2+4$ content = 2. $gcd(2,4)=2$
	$3x^2 + 5$ content = 1 gcd(3,5)=1.
	Market Valley
-	GAUSS'S LEMMA: The product of 2 primitive polynomials is primitive.
	The state of the s

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wat an fast a transast a hart seen as the way
 Let g(x), h(x) be two primitive polynomials.
 f(x)= g(x) · h(x).
                                            =+(x) = (10). h, (x).
 GOAL: Prove f(x) is primitive.
  cont (f) & content of polynomial.
  If f(x) is not primitive, cont(f) +1, cont(f) eIN.
  Let p be a prime divisor.
  Let I(x), g(x) and h(x) be the polynomials obtained from f(x), g(x) and h(x)
  by reducing the coefficients mode.
   f(x) = g(x) h(x)
  By plant (f) f(x) +0.
  But qw. h(x) ≠0 (>≠).
* EXAMPLE
  x2-2 is irreducible over I and Q.
  x2-2 is reducible over Q(NZ)
  x2-2= (x-N2)(x+N2)
- INBOREM: Let f(x) & Z[x]. If f(x) is reducible over Q, f(x) is reducible over Z
  NOTE: The converse is not true, Eg for=2x2+4.
  PROOF
  f(x)=g(x)h(x), g(x),h(x) EQ[x].
  Let a be the least common multiple of the denominators of the coefficients
   g(x) = 50 ti xi b, Gi & 12. gcd (bi, ci)=1.
   a = [ Cm, Cm-1, ..., c, co] = least common multiple.
   h(x) = $ = x d, c, e Z. gcd(d, c,)=1.
   b= [ex, ex-1, -.., e, eo]
   ab. f(x)= abg(x), h(x)
          = (m g(x)) x (bh(x))
                     2 X1
              TIX]
                                                  g(x), h(x) & Z[x]
   cont(aga)) = \epsilon_i \Rightarrow a \cdot g(x) = c_i \cdot g(x)
   writ(bh(x) = c2 ⇒ b. h,(x) = c2. h(x)
                                                                    Hilroy
  = g,(x), h,(x) are primitive
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	Get ab. fox) = [ag. (x)][b	ha)]=qg, a), 6h, (x)
	primitive	$= c_1 c_2 \left( g_1(x) h_1(x) \right)$
		primitive.
	$\Rightarrow f(x) = g_i(x) \cdot h_i(x)$	2 of times and a spile spile
	,	the service is the suppose of Charles
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4. HW appeals 5. Happy 61-Tholong to me? 1. HW2 returned 2. HW3 due 3. HWY assigned Math 401 Pols Eggs Fields, Jan 30 2008, week 4. Agenda 1. homomorphisms -annaying was & 150. 72m. on boald det at homomo, annoying properties. 2. An aside on domains an fillds. Continue as on Jan 31, 2007. 3. palynomials, division, roots.

\* Web only HW41 Math 401 Pols, Egns, Fields, Jan 31 2007 Week 4 Reminder 1. IF O.R 75 is a ring homomorphism the Moth "pathoras". Ker & is an ideal in R 1. set theoretic andry 2. vank-nullity Am. 32. R/Ker & = Q(R) The First 150. That 3. Every ideal is a ternely if ACR is and well, TI'R - R/A has kerTT = A. Claim R with unity = >1.7 -> R, by nt->n.1 is a homon cor char R=n >0 -> R contains a subring-150. to Ith Charles = > R contains -11- 7 COLE & Field: Char F-P => F>2/p 2/3 how = chr F=0 =) F=0 (). The field of qualitation then there is to how. Contains an isomorphic copy of D. Def R[X] (R commytative), dup jevolgation. Ihm Da domain => DZX). too; dug fig = dug F+dug. Then F, 9 EFEXT, 970 => DI 9, reflect for F = 94+11

L deg r < deg g. 9: "The quotient for F/9" Cor / FEFTX] => F/a) is the remainder for F/x-a COC2 a is a root of F (3) (x-a) is a factor

1	DeE Zero OF a pot., multiplicity OF 1200.
	cor. A polynomial of degree a over a field has
	cor. A polynomial of degree nover a field has
	Def PID.  Then FEX 1's a PID'; if I is an ideal in FD.
-	The Total it is an all the total
	I= <9> iff 9 is a non-zero chement of I
	OF minmal degree.
	Example IRIXIXX+17 = C using  \$\phi: \rho \mathcal{P} \rightarrow \rho(i) \ranger the First 150. thm.
	Diploppi) & the First 150. thm.

class photo to day of (Al first break) Mith 401 Pols, Egns, Fields, Jan 24 2007 Week 3 I deal A-A = A, KA=A AKEA; K/A makes sensell Resimpatorian This R/A is a Johnan IFE A is prime. Thing R/A is a field iff A is maximal. PHOMOMOrphisms: philosophy: objects, games, sets, groups Examples 3. 146/1-5 (6a) more in text 4. Zh, -53 Zho 1 Z Marity foll 2 1/R/27/P/3/1/R Annoying Properties 1.  $\phi(nr)=n \phi$ ;  $\phi(rr)=\phi(r)^n$ for  $\phi: R \to S$  2.  $\phi(A)$  is a sub-ring (imp for) sub-ring (imp for) sub-ring (imp for)  $\phi(A)$  is  $\phi(A)$  in ideal (kery two) p(nr)=nø; p(rn)=p(r)n 3. A ideal; is play or itel? No med & intoly
4. \$\phi(B) an ideal (key) too) 5 R commut = ) Ø(R) too 6. R his a unity, SHOY, of isont => \$(1) is ket welly 7. 0 is 150, if ker \$= 50 \ \ in \$=5 This Rkerp = P(R) This Every ideal ACR is a kernel; TIR-PAKETIFA. This R with unity => I -> R by a -> n.1 is a homomorphism. Cor char R=170 => Recordains a subject 150, to In charR=0 => R contains -11-COV FAFIELD; CharF=P => F>Z/P the IFD is an integral derin, then there is a field

F that contains D as a subring.

· · /cont.

	Ring of polynomials.
*.	Det REXT (R commatative) deg P
*	Then Da domain => D[x] too.
	Im Long Livisian in FIX
,	

Mits 401 Pols, Egns, Fields, Jan 23 2008, Week 3 REXIXX+17 = [= (18 +1) 1. The meaning of the lhs. Ideals: A-ACA, AA.CA, A'RCA RAFA' R/Amiles subring ideal. Sensel Prime & maximal ideals as on Jan 17, 2007 Homomorphisms as on Jan 244, 2007

1. class photo @ break

Office hours: Chao Li, TA: The 12-2, 55107/ DBN Wed 10:30-11:30, RA 6178

Math 401 Pols, Egns, Fields, Jan 17 2007, Week 2. Ring: X - Assoc, distributivo. Sometimes "unity" "inverses".
IE exist, they are unique. Subring: A subset which is aring = desd under x, -Zero divisor: a.b=0 but a+0,5+0 integral domain: commetative with andy kno zero divisors; ac-bc, c Finald tix both make aboling gaps (+distributive) Then A finite integral domain is a field of I/p is a field. Thm: IF D is an integral Lormin, there D is O or 60 ovc/ Table 13.2 I don't (two sided) ( Va, both A n-bea meAl weA. Framples Job, 12, 507, <176/8/XJ, <4,276/21/2 R/A = Equiv chosses and/or cosets. I more examples Framples R/404, Z/nZ, IRIX3/<x2+17 (+ext) Det prime & maximal ideals. (of commutative rings)

I xample NaCA is prime if the is.

Example

Exampl Thro RIA is an integral domain iff A is prime. Thm R/A is a field iff A is maximal.

Ringh	momorphice	ac in	Srief.		
17.5	0. 10. 11. 11. 11.	1) . ( )	,		
,					
				,	

**TABLE 13.2** Summary of Rings and Their Properties

Ring	Form of Element	Unity	Commutative	Integral Domain	Field	Characteristic
Z	k	1	Yes	Yes	No	0
$Z_n$ , <i>n</i> composite	k	1	Yes	No	No	n
$Z_p$ , p prime	k ·	1	Yes	Yes	Yes	P
Z[x]	$a_n x^n + \cdot \cdot \cdot +$	f(x) = 1	Yes	Yes	No	0
	$a_1 x + a_0$					
nZ, $n > 1$	nk	None	Yes	No	No	0
$M_2(Z)$	$\begin{bmatrix} a & b \\ c & d \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	No	No	No	0
$M_2(2Z)$	$\begin{bmatrix} 2a & 2b \\ 2c & 2d \end{bmatrix}$	None	No	No	No	0
Z[i]	a + bi	1	Yes	Yes	No	0
$Z_3[i]$	$a + bi$ ; $a, b \in Z_3$	1	Yes	Yes	Yes	3
$Z[\sqrt{2}]$	$a + b\sqrt{2}$ ; $a, b \in Z$	1	Yes	Yes	No	0
$Q[\sqrt{2}]$	$a + b\sqrt{2}$ ; $a, b \in Q$	1	Yes	Yes	Yes	0
$Z \oplus Z$	(a,b)	(1, 1)	Yes	No	No	0

Math 401 Pols Egns Fields, Jan 9 2007 week 1. (b,2) About Galois jabout this class. Why rings 2 Mb. numbers form a ring Det A ving R is a non-empty set of two binary of (a,b) to ats and (a,b) to all a b, c. 1. A+5=6+a 3. an element OFR is given, 2. (a+4)+C=Va+(b+c) Such Pait 0+a=a 10 Ha J(-a) sit a+(-a)=0. 5(1, a(bc) = (ab)c 6. a(b+c) = (b+c)a = ...Def. commutative ving, ving w/ unity. Examples as in Table 13.2: Ihm 1 1. a.o=0.a=0 2. a(-b)=(ab) 3. (-a)(-b)-ab 14 a(b-c)=ab-ac if unity, 5. (-1) a=-a 6. (-1)(-1)=1. Thm2 If a ring his a unit, it is unique.

If an element of a ring his an inverse, it is unique. , Carcillestions, Foro Sivisors, integral dominis (in communitative communitative ing (mgs) Wight: ( Back to Ta5h 32 no ordivisors

Field: Commutative ving W/ Vnits in which The A Finite integeral domain is a field. Cor 2/p is a field. thor R it R has a unky. Ihm IF D is a domain, chard 150 or a prime. Week 2: repent 07-401/Week 2. Notes HWZ on Wel R/A is an integral domain if A is prime:

## 08-401/About This Class

### From Drorbn

## **Contents**

- 1 Crucial Information
- 2 Abstract
- 3 Text Book(s)
- 4 Plan
- 5 Wiki
- 6 Marking Scheme
  - 6.1 The Term Test
  - 6.2 Homework
- 7 Good Deeds
- 8 Class Photo
- 9 On Galois

### **Crucial Information**

**Agenda:** Follow Évariste Galois (http://en.wikipedia.org/wiki/Galois) to the top of mathematics' first mountain.

Classes: Wednesdays 6-9PM (OMG) at Sidney Smith 1086

(http://www.osm.utoronto.ca/cgi-bin/class\_spec/spec03?bldg=SS&room=1086).

**Instructor:** Dror Bar-Natan (http://www.math.toronto.edu/~drorbn/), drorbn@math.toronto.edu, Bahen 6178, 416-946-5438. Office hours: Tuesdays 12:30-1:30 and most Thursdays 1-2 (lunchtime, at the math lounge or at my office), or by appointment.

**Teaching Assistant:** Yichao Zhang, zhangyichao2002@hotmail.com. Office hours: Tuesdays 1-3 at the Math Aid Centre, Sidney Smith 1071.

Grades. All grades will be on CCNet (http://ccnet.utoronto.ca/20081/mat401h1s/).

URL: http://katlas.math.toronto.edu/drorbn/index.php?title=08-401.

### **Abstract**

Taken from the Faculty of Arts and Science Calendar (http://www.artsandscience.utoronto.ca/ofr/calendar/crs\_mat.htm)

Commutative rings; quotient rings. Construction of the rationals. Polynomial algebra. Fields and Galois theory: Field extensions, adjunction of roots of a polynomial. Constructibility, trisection of angles, construction of regular polygons. Galois groups of polynomials, in particular cubics, quartics. Insolvability of quintics by radicals.

■ Prerequisite: MAT224H1 (Linear Algebra II), MAT235Y1/MAT237Y1 (Calculus II/Multivariable Calculus),

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11	Mar 26	HW9, Notes
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13	Apr 9	Notes
S	Apr 14-18	Study Period
F		Final
Image:08-401 Class Photo.jpg Add your name / see who's in!		
Register of Good Deeds		

MAT246H1/MAT257Y1 (Concepts in Abstract Mathematics/Analysis II).

■ Exclusion: MAT347Y1 (Groups, Rings and Fields).

## Text Book(s)

- (Required) J. A. Gallian, "Contemporary Abstract Algebra", chapters 12-17, 20-23 and 31-33 (approx.).
- (Recommended) D. S. Dummit and R. M. Foote, "Abstract Algebra", chapters 7, 8, 9, 13, 14.
- (Suggested) T. Hungerford, "Abstract Algebra, an Introduction".

#### Plan

I will aim to cover the above-mentioned 13 chapters of Gallian's book at a bit faster than one per week, so as to leave us some time for extras at the end, but we may fall back to a rate of just one chapter a week or even less. If so, chapters 23 and 31 will be the first candidates for skipping.

### Wiki

The class web site is a wiki, as in Wikipedia (http://www.wikipedia.org) - meaning that anyone can and is welcome to edit almost anything and in particular, students can post notes, comments, pictures, whatever. Some rules, though -

- This wiki is a part of my (Dror's) academic web page. All postings on it must be class-related (or related to one of the other projects I'm involved with).
- I (Dror) will allow myself to exercise editorial control, when necessary.
- The titles of all pages related to this class should begin with "08-401/" or with "08-401-", just like the title of this page.

To edit, you must have a wiki account. To get one email a request to Dror at drorbn@math.toronto.edu, and include:

- Your first and last name.
- Your preferred user id.
- Your email address, if different from the address you've used for this email.

Some further editing help is available at Help:Contents.

## **Marking Scheme**

There will be one term test (25% of the total grade) and a final exam (50%), as well as about 10 homework assignments (25%).

### The Term Test

The term test will take place in class on February 28. A student who misses the term test without providing a valid reason (for example, a doctor's note) within one week of the test will receive a mark of 0 on the term test. There will be no make-up term test. If a student misses the term test for a valid reason, the weight of the problem sets will increase to 35% and the weight of the final exam to 65%.

### Homework

Assignments will be posted on the course web page approximately on the weeks shown in the class timeline. Typically an "in preparation" version of any assignment will be posted a bit before class and the "in preparation" tag will be removed shortly after class, once our progress in class is precisely measured. Assignments will be due in class a week after they are assigned and they will be marked by the TA, usually within another week. All students (including those

who join the course late) will receive a mark of 0 on each assignment not handed in; though to allow you some leeway, in computing the homework grade your worst two assignments will not count. I encourage you to discuss the assignments with other students or even browse the web, so long as you do at least some of the thinking on your own and you write up your own solutions. Remember that cheating is always possible and may increase your homework grade a bit. But it will hurt your exam grades a lot more.

### **Good Deeds**

Students will be able to earn up to 25 "good deeds" points throughout the year for doing services to the class as a whole. There is no pre-set system for awarding these points, but the following will definitely count:

- Drawing a beautiful picture to illustrate a point discussed in class and posting it on this site.
- Taking class notes in nice handwriting, scanning them and posting them here.
- Typing up or formatting somebody else's class notes, correcting them or expanding them in any way.
- Writing an essay expanding on anything mentioned in class and posting it here; correcting or expanding somebody else's article.
- Doing anything on our 08-401/To do list.
- Any other service to the class as a whole.

Good deed points will count towards your final grade! If you got n of those, they are solidly your and the formula for the final grade below will only be applied to the remaining 100-n points. So if you got 25 good deed points (say) and your final grade is 80, I will report your grade as 25+80(100-25)/100=85. Yet you can get an overall 100 even without doing a single good deed.

#### Class Photo

To help me learn your names, I will take a class photo on the third week of classes. I will post the picture on the class' web site and you will be *required* to identify yourself on the Class Photo page of this wiki.

### On Galois

The first paragraph of the Wikipedia entry (http://en.wikipedia.org/wiki/Galois) on Galois:

Évariste Galois (IPA: [evalist ga lwa]; October 25, 1811 – May 31, 1832) was a French mathematician born in Bourg-la-Reine. While still in his teens, he was able to determine a necessary and sufficient condition for a polynomial to be solvable by radicals, thereby solving a long-standing problem. His work laid the foundations for Galois theory, a major branch of abstract algebra, and the subfield of Galois connections. He was the first to use the word "group" (French: groupe) as a technical term in mathematics to represent a group of permutations. A radical Republican during the monarchy of Louis Philippe in



Galois at the age of fifteen from the pencil of a classmate. He was young-looking for his age and had black hair.

France, he died from wounds suffered in a duel under murky circumstances at the age of twenty.

Retrieved from "http://katlas.math.toronto.edu/drorbn/index.php?title=08-401/About\_This\_Class"

■ This page was last modified 23:10, 8 January 2008.

# 08-401/Homework Assignment 1

## From Drorbn

## In Preparation

The information below is preliminary and cannot be trusted! (v)

## Reading

Read chapters 12 and 13 of Gallian's book three times:

- First time as if you were reading a novel quickly and without too much attention to detail, just to learn what the main keywords and concepts and goals are.
- Second time like you were studying for an exam on the subject slowly and not skipping anything, verifying every little detail.
- And then a third time, again at a quicker pace, to remind yourself of the bigger picture all those little details are there to paint.

## **Doing**

Solve problems 1, S2, 8, 12, S13, S19, 20, S22, 33, 47 and 50 in Chapter 12 of Gallian's book and problems 4, 7, 12, S13, 16, S24 and 33 in Chapter 13 of the ame book, but submit only the solutions of the problems marked with the letter "S".

### **Due Date**

This assignment is due in class on Wednesday January 16, 2007.

Retrieved from "http://katlas.math.toronto.edu/drorbn/index.php?title=08-401/Homework\_Assignment\_1"

■ This page was last modified 14:59, 8 January 2008.

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S	Apr 14-18	Study Period	
F		Final	
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Add your name / see who's in!

Register of Good Deeds

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O: About this class. - -Math 401 Pols, Egns, Fields, Jan 1002007 Weck 1 -() Examples 12, 1/n, 12[X], M2(Z), 210, 4[J, C Det BD: A ving R is a non-empty set with two binning ges (a, b) to a (b and (a, b)) = 96 5.7. for all a, b, c, 3. Ha f (-a) s.+ a+(-a)=0 S. Malber Cable a (6+0) = a6+ac (6+0/a=61+00a 'Def direct supp. Thm 1. 20=06=0 2. 2(-6)=1-166) 3. (-a)(-b)=06 4-2(6-c)=26-26 5. (B) if 3168 5+34-2, 400) (1)a=-C, (-1)(-1)=1. Ihm If a ving his a unity, it is unique; if an along his an inverse, it is unique. Subring: A subset which is a ring until some off.

Logal Bunder subsection & ander mult,

hor-impty subset. Zero División integral deresas, 90 over above chaples in commutative via concentration. Field: Commy fative ring with anity in which

the A finite integal domain is a Field. that R Char R IF R has a unity. Thm If DA is an an integral domain, chard is o or a Mine. 90 our fille 13.2,