Vid on if you can!

The Strongest Genuinely Computable Knot Invariant ~~Since~~ In 2024

The First International On-line Knot Theory Congress

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Abstract. “Genuinely computable” means we have computed it for random knots with over 300 crossings. “Strongest” means it separates prime knots with up to 15 crossings better than the less-computable HOMFLY-PT and Khovanov homology taken together. And hey, it’s also meaningful and fun.
Continues Rozansky, Garoufalidis, Kricker, and Ohtsuki, joint with van der Veen.

These slides and the code within are online at ωεβ:=http://drorbn.net/ktc25

(I wish all speakers were making their slides available **before / for** their talks).

(I'll post the video there too)

A paper-in-progress is at ωεβ/Theta.

If you can, please turn your video on!

Happy birthday, dear Lou!

Lou Kauffman at MSRI, March 1991

Acknowledgement.

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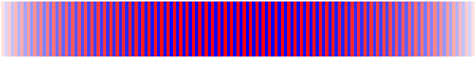
The Strongest Genuinely Computable Knot Invariant ~~Since~~ In 2024

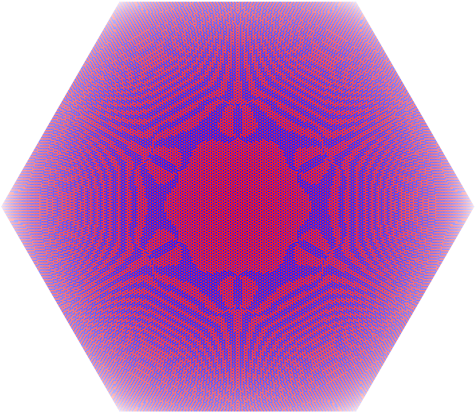
Strongest? Genuinely Computable?

Strongest.

Testing $\Theta = (\Delta, \theta)$ on prime knots up to mirrors and reversals, counting the number of distinct values (with deficits in parenthesis): (ρ_1: [Ro1, Ro2, Ro3, Ov, BV1])

	knots	(H, Kh)	(Δ, ρ_1)	$\Theta = (\Delta, \theta)$	(Δ, θ, ρ_2)	all together
reign		2005-22	2022-24	2024	2025-	
xing $\leq$ 10	249	248 (1)	249 (0)	249 (0)	249(0)	249 (0)
xing $\leq$ 11	801	771 (30)	787 (14)	798 (3)	798 (3)	798 (3)
xing $\leq$ 12	2,977	(214)	(95)	(19)	(10)	(10)
xing $\leq$ 13	12,965	(1,771)	(959)	(194)	(169)	(169)
xing $\leq$ 14	59,937	(10,788)	(6,253)	(1,118)	(982)	(981)
xing $\leq$ 15	313,230	(70,245)	(42,914)	(6,758)	(6,341)	(6,337)



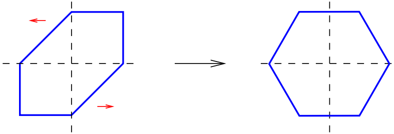


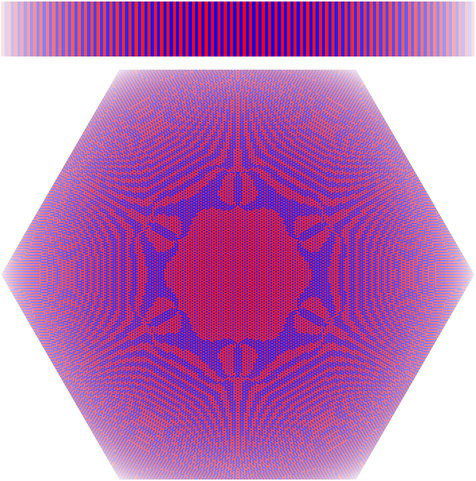
Genuinely Computable. Here's Θ on a random 300 crossing knot (from [DHOEBL]). For almost every other knot invariant, that's science fiction.

Gukov: Should take 300 years if Moore's law persists.

Us: A few hours on a laptop, 0 GPUs.

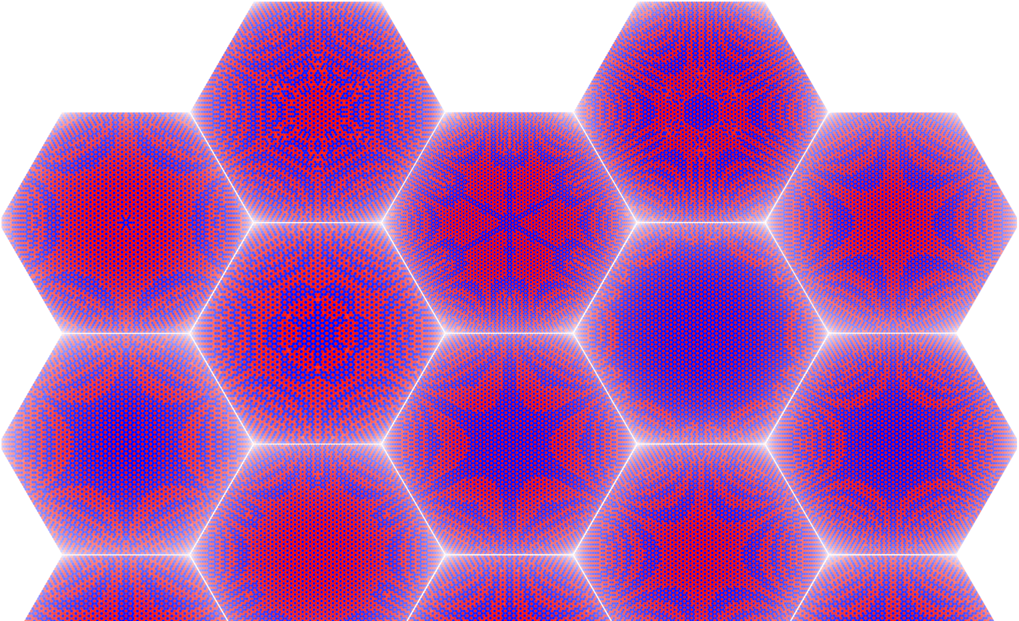
(Δ, Θ)



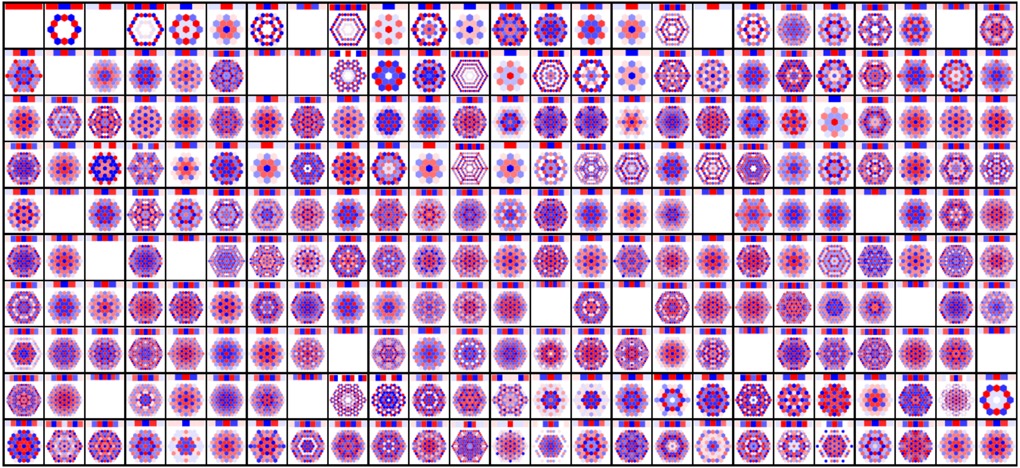


Fun. There's so much more to see in 2D pictures than in 1D ones! Yet almost nothing of the patterns you see we know how to prove. We'll have fun with that over the next few years. Would you join?

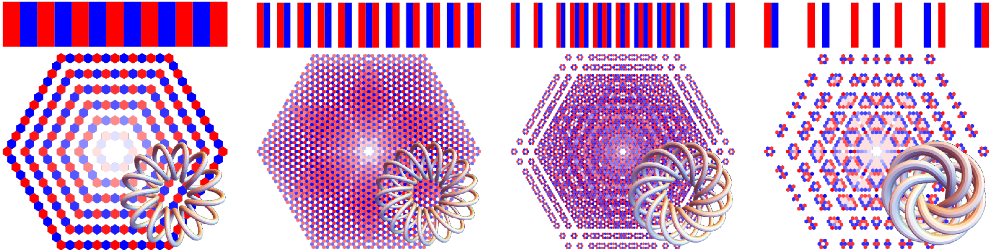
Random knots (from [DHOEBL]) with 101–115 crossings:

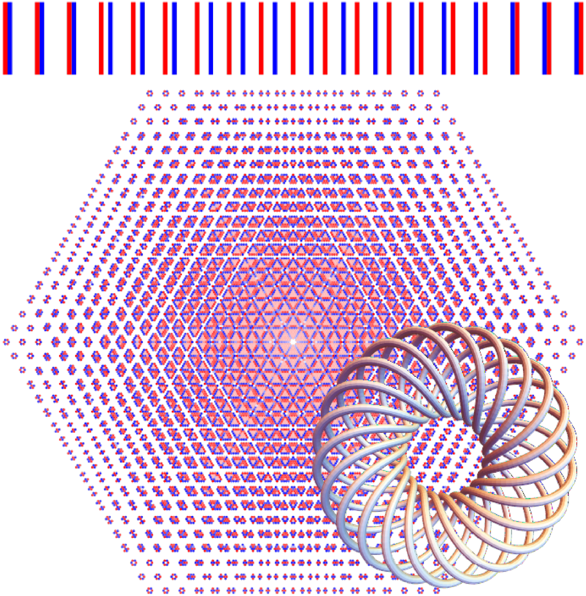


The Rolfsen Table:



The torus knots $TK_{13/2}$, $TK_{17/3}$, $TK_{13/5}$, and $TK_{7/6}$:





The torus knot $TK_{22/7}$:

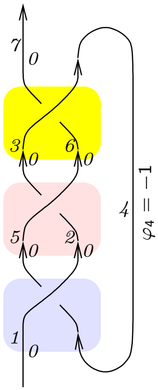
Meaningful.

θ gives a genus bound (unproven yet with confidence). We hope (with reason) it says something about ribbon knots.

Convention.

T, T_1, and T_2 are indeterminates and $T_3 := T_1 T_2$.

Preparation. Draw an n-crossing knot K as a diagram D as on the right: all crossings face up, and the edges are marked with a running index $k \in \{1, \ldots, 2n+1\}$ and with rotation numbers φ_k.



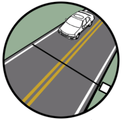
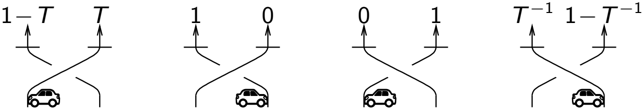


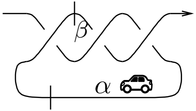
image credits: diamondtraffic.com

$p = 1 - T^s$

image credits: Dall-E

Model T Traffic Rules. Cars always drive forward. When a car crosses over a sign-s bridge it goes through with (algebraic) probability $T^s \sim 1$, but falls off with probability $1 - T^s \sim 0$. At the very end, cars fall off and disappear. On various edges traffic counters are placed. See also [Jo, LTW].

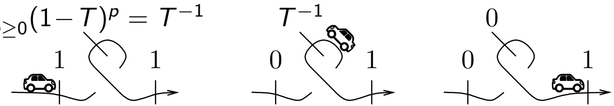




Definition. The traffic function $G=(g_{\alpha\beta})$ (also, the Green function or the two-point function) is the reading of a traffic counter at β, if car traffic is injected at α (if $\alpha=\beta$, the counter is after the injection point). There are also model-T_ν traffic functions $G_\nu=(g_{\nu\alpha\beta})$ for $\nu=1,2,3$.

Example.

$\sum_{p\geq 0}(1-T)^p=T^{-1}$



$$G=\begin{pmatrix}1 & T^{-1} & 1\\ 0 & T^{-1} & 1\\ 0 & 0 & 1\end{pmatrix}$$

$1+(1-T)+(1-T)^2+\ldots$

Given crossings $c=(s,i,j)$, $c_0=(s_0,i_0,j_0)$, and $c_1=(s_1,i_1,j_1)$, let

$$
\begin{aligned}
F_1(c) = s\,[1/2 &- g_{3ii} + T_2^s g_{1ii}g_{2ji} - T_2^s g_{3jj}g_{2ji} - (T_2^s-1)g_{3ii}g_{2ji} \\
&+(T_3^s-1)g_{2ji}g_{3ji} - g_{1ii}g_{2jj} + 2g_{3ii}g_{2jj} + g_{1ii}g_{3jj} - g_{2ii}g_{3jj}] \\
&+ \frac{s}{T_2^s-1}\,[(T_1^s-1)\,T_2^s\,(g_{3jj}g_{1ji} - g_{2jj}g_{1ji} + T_2^s g_{1ji}g_{2ji}) \\
&\quad + (T_3^s-1)\,(g_{3ji} - T_2^s g_{1ii}g_{3ji} + g_{2ij}g_{3ji} + (T_2^s-2)g_{2jj}g_{3ji}) \\
&\quad - (T_1^s-1)(T_2^s+1)(T_3^s-1)g_{1ji}g_{3ji}]
\end{aligned}
$$

$$
F_2(c_0,c_1) = \frac{s_1(T_1^{s_0}-1)(T_3^{s_1}-1)g_{1j_1i_0}g_{3j_0i_1}}{T_2^{s_1}-1}\,(T_2^{s_0}g_{2i_1i_0} + g_{2j_1j_0} - T_2^{s_0}g_{2j_1i_0} - g_{2i_1j_0})
$$

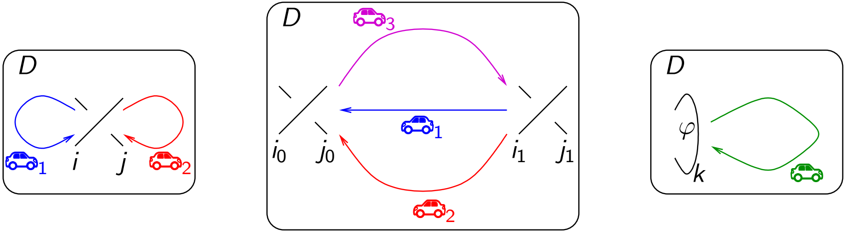
$$
F_3(\varphi_k,k) = \varphi_k(g_{3kk}-1/2)
$$

(Computers don't care!)

Main Theorem.

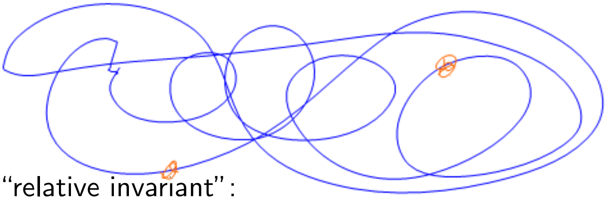
The following is a knot invariant: (the Δ_ν are normalizations discussed later)

$$\theta(D) := \Delta_1\Delta_2\Delta_3\left(\sum_c F_1(c) + \sum_{c_0,c_1} F_2(c_0,c_1) + \sum_k F_3(\varphi_k,k)\right).$$

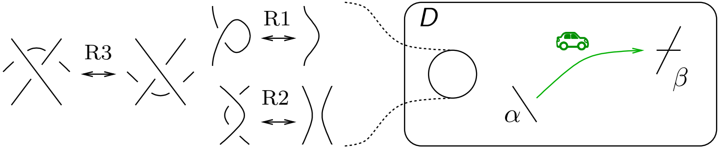


If these pictures remind you of Feynman diagrams, it's because they are Feynman diagrams [BN2].

Lemma 1.

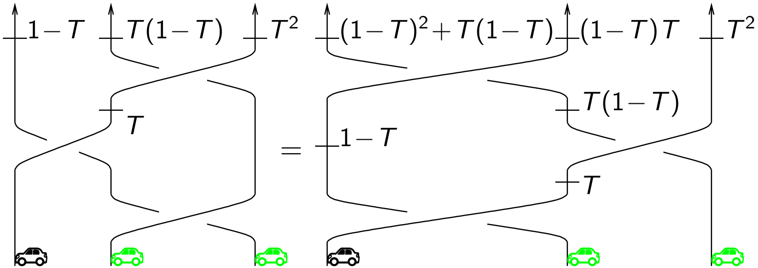


The traffic function $g_{\alpha\beta}$ is a "relative invariant":



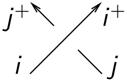
(There is some small print for R1 and R2 which change the numbering of the edges and sometimes collapse a pair of edges into one)

Proof.



Lemma 2.

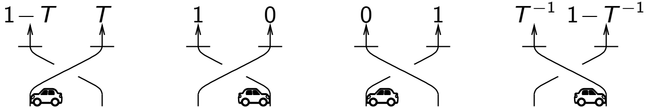
$\underline{\underline{A}}G = I$



With $k^+ := k+1$, the "g-rules" hold near a crossing $c=(s,i,j)$:

$$g_{j\beta} = g_{j^+\beta} + \delta_{j\beta} \quad g_{i\beta} = T^s g_{i^+\beta} + (1-T^s) g_{j^+\beta} + \delta_{i\beta} \quad g_{2n^+,\beta} = \delta_{2n^+,\beta}$$

$$g_{\alpha i^+} = T^s g_{\alpha i} + \delta_{\alpha i^+} \quad g_{\alpha j^+} = g_{\alpha j} + (1-T^s) g_{\alpha i} + \delta_{\alpha j^+} \quad g_{\alpha,1} = \delta_{\alpha,1}$$



Corollary 1.

$G = A^{-1}$

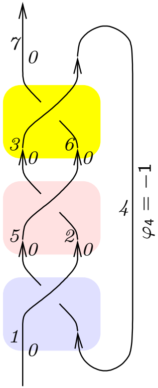
G is easily computable, for $AG = I$ $(= GA)$, with A the $(2n+1)\times(2n+1)$ identity matrix with additional contributions:

$c = (s, i, j) \mapsto$

A	col i^+	col j^+
row i	$-T^s$	$T^s - 1$
row j	0	-1

For the trefoil example, we have:

$$A = \begin{pmatrix} 1 & -T & 0 & 0 & T-1 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -T & 0 & 0 & T-1 \\ 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & T-1 & 0 & 1 & -T & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$



And so,

$$G=\begin{pmatrix} 1 & T & 1 & T & 1 & T & 1 \\ 0 & 1 & \frac{1}{T^2-T+1} & \frac{T}{T^2-T+1} & \frac{T}{T^2-T+1} & \frac{T^2}{T^2-T+1} & 1 \\ 0 & 0 & \frac{1}{T^2-T+1} & \frac{T}{T^2-T+1} & \frac{T}{T^2-T+1} & \frac{T^2}{T^2-T+1} & 1 \\ 0 & 0 & \frac{1-T}{T^2-T+1} & \frac{1}{T^2-T+1} & \frac{1}{T^2-T+1} & \frac{T}{T^2-T+1} & 1 \\ 0 & 0 & \frac{1-T}{T^2-T+1} & -\frac{(T-1)T}{T^2-T+1} & \frac{1}{T^2-T+1} & \frac{T}{T^2-T+1} & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Note.

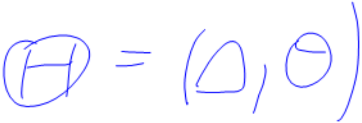
The Alexander polynomial Δ is given by

$$\Delta = T^{(-\varphi-w)/2}\det(A),$$

with

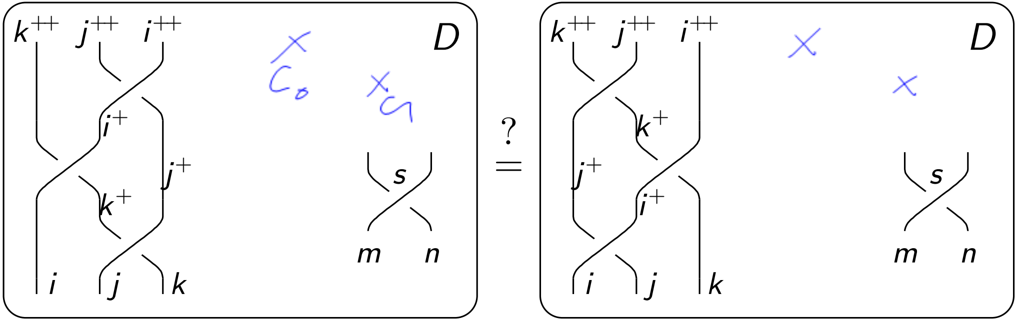
$$\varphi = \sum_k \varphi_k, \qquad w = \sum_c s.$$

We also set $\Delta_\nu := \Delta(T_\nu)$ for $\nu = 1, 2, 3$. This defines and explains the normalization factors in the Main Theorem.



Corollary 2.

Proving invariance is easy:



Invariance under R3

This is Theta.nb of http://drorbn.net/ktc25/ap.

```
Once[<< KnotTheory`; << Rot.m; << PolyPlot.m];
```

```
Loading KnotTheory` version of October 29, 2024, 10:29:52.1301.
Read more at http://katlas.org/wiki/KnotTheory.
Loading Rot.m from http://drorbn.net/ktc25/ap to compute rotation numbers.
Loading PolyPlot.m from
  http://drorbn.net/ktc25/ap to plot 2-variable polynomials.
```

```
T3 = T1 T2;
CF[ℰ_] := Expand@Collect[ℰ, g__, F] /. F → Factor;
```

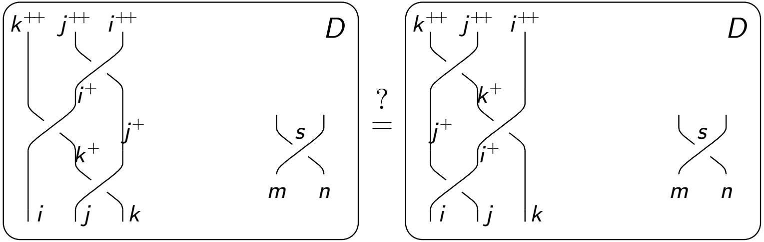
$$F_1[\{s\_,\ i\_,\ j\_\}] = \mathrm{CF}\Big[s\Big(1/2 - g_{3ii} + T_2^s g_{1ii} g_{2ji} - g_{1ii} g_{2jj} - (T_2^s - 1) g_{2ji} g_{3ii} + 2 g_{2jj} g_{3ii} - (1 - T_3^s) g_{2ji} g_{3ji} - g_{2ii} g_{3jj} - T_2^s g_{2ji} g_{3jj} + g_{1ii} g_{3jj} + \big((T_1^s - 1) g_{1ji} (T_2^{2s} g_{2ji} - T_2^s g_{2jj} + T_2^s g_{3jj}) + (T_3^s - 1) g_{3ji} (1 - T_2^s g_{1ii} - (T_1^s - 1)(T_2^s + 1) g_{1ji} + (T_2^s - 2) g_{2jj} + g_{2ij})\big) / (T_2^s - 1)\Big)\Big];$$

$$F_2[\{s0\_,\ i0\_,\ j0\_\},\ \{s1\_,\ i1\_,\ j1\_\}] := \mathrm{CF}\Big[s1\,(T_1^{s0} - 1)\,(T_2^{s1} - 1)^{-1}\,(T_3^{s1} - 1)\, g_{1,j1,i0}\, g_{3,j0,i1} \big((T_2^{s0} g_{2,i1,i0} - g_{2,i1,j0}) - (T_2^{s0} g_{2,j1,i0} - g_{2,j1,j0})\big)\Big]$$

$$F_3[\varphi\_,\ k\_] = -\varphi / 2 + \varphi\, g_{3kk};$$

$$\delta_{i\_,j\_} := \mathrm{If}[i === j, 1, 0];$$

$$\begin{aligned} gR_{s\_,i\_,j\_} := \{ & g_{\nu\_ j\beta\_} :\to g_{\nu j^+\beta} + \delta_{j\beta},\ g_{\nu\_ i\beta\_} :\to T_\nu^s\, g_{\nu i^+\beta} + (1 - T_\nu^s)\, g_{\nu j^+\beta} + \delta_{i\beta}, \\ & g_{\nu\_\alpha\_ i^+} :\to T_\nu^s\, g_{\nu\alpha i} + \delta_{\alpha i^+},\ g_{\nu\_\alpha\_ j^+} :\to g_{\nu\alpha j} + (1 - T_\nu^s)\, g_{\nu\alpha i} + \delta_{\alpha j^+} \\ \} & \end{aligned}$$




```
DSum[Cs___] := Sum[F_1[c], {c, {Cs}}] +
  Sum[F_2[c0, c1], {c0, {Cs}}, {c1, {Cs}}]
lhs = DSum[{1, j, k}, {1, i, k^+}, {1, i^+, j^+}, {s, m, n}] //.
   gR_{1,j,k} ∪ gR_{1,i,k^+} ∪ gR_{1,i^+,j^+};
rhs = DSum[{1, i, j}, {1, i^+, k}, {1, j^+, k^+}, {s, m, n}] //.
   gR_{1,i,j} ∪ gR_{1,i^+,k} ∪ gR_{1,j^+,k^+};
Simplify[lhs == rhs]
True
```

The Main Program

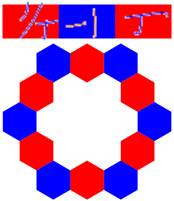
```
Θ[K_] := Module[{Cs, φ, n, A, Δ, G, ev, θ},
   {Cs, φ} = Rot[K]; n = Length[Cs];
   A = IdentityMatrix[2 n + 1];
   Cases[Cs, {s_, i_, j_} :> (A[[{i, j}, {i + 1, j + 1}]] += ( -T^s  T^s - 1
                                                                 0      -1   ))];
   Δ = T^((-Total[φ]-Total[Cs[[All,1]]])/2) Det[A];
   G = Inverse[A];
   ev[ℰ_] := Factor[ℰ /. g_{ν_,α_,β_} :> (G[[α, β]] /. T → T_ν)];
   θ = ev[Sum_{k=1}^{n} F_1[Cs[[k]]]];
   θ += ev[Sum_{k1=1}^{n} Sum_{k2=1}^{n} F_2[Cs[[k1]], Cs[[k2]]]];

   θ += ev[Sum_{k=1}^{2 n} F_3[φ[[k]], k]];
   Factor@{Δ, (Δ /. T → T_1) (Δ /. T → T_2) (Δ /. T → T_3) θ}];
```

The Trefoil Knot

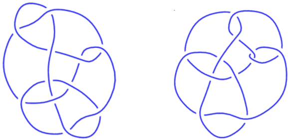
```
Θ[Knot[3, 1]] // Expand
```

$$\left\{-1+\frac{1}{T}+T,\ -\frac{1}{T_1^2}-T_1^2-\frac{1}{T_2^2}-\frac{1}{T_1^2\,T_2^2}+\frac{1}{T_1\,T_2^2}+\frac{1}{T_1^2\,T_2}+\frac{T_1}{T_2}+\frac{T_2}{T_1}+T_1^2\,T_2-T_2^2+T_1\,T_2^2-T_1^2\,T_2^2\right\}$$

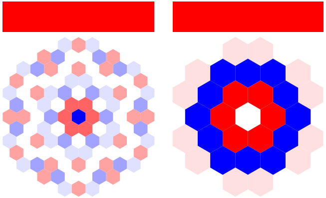
```
PolyPlot[Θ[Knot[3, 1]], ImageSize → Tiny]
```



The Conway and Kinoshita-Terasaka Knots



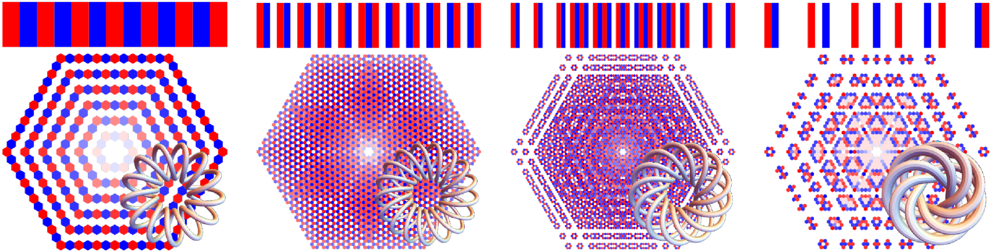
```
GraphicsRow[PolyPlot[Θ[Knot[#]], ImageSize → Tiny] & /@
  {"K11n34", "K11n42"}]
```



(Note that the genus of the Conway knot appears to be bigger than the genus of Kinoshita-Terasaka)

The Torus Knots $TK_{13/2}$, $TK_{17/3}$, $TK_{13,5}$, and $TK_{7,6}$

```
GraphicsRow[ImageCompose[
    PolyPlot[Θ[TorusKnot @@ #], ImageSize → 480],
    TubePlot[TorusKnot @@ #, ImageSize → 240],
    {Right, Bottom}, {Right, Bottom}
  ] & /@ {{13, 2}, {17, 3}, {13, 5}, {7, 6}}]
```



Questions, Conjectures, Expectations, Dreams.

Question 1.

What's the relationship between Θ and the Garoufalidis-Kashaev invariants [GK, GL]?

Conjecture 2.

On classical (non-virtual) knots, θ always has hexagonal (D_6) symmetry.

Conjecture 3.

$\mathfrak{g}_\epsilon$ $\qquad$ $\mathfrak{b}^+ \ltimes \mathfrak{b}^-$

θ is the ϵ^1 contribution to the "solvable approximation" of the sl_3 universal invariant, obtained by running the quantization machinery on the double $\mathcal{D}(\mathfrak{b}, b, \epsilon\delta)$, where $\mathfrak{b}$ is the Borel subalgebra of sl_3, b is the bracket of $\mathfrak{b}$, and δ the cobracket. See [BV2, BN1, Sch]

Conjecture 4.

θ is equal to the "two-loop contribution to the Kontsevich Integral", as studied by Garoufalidis, Rozansky, Kricker, and in great detail by Ohtsuki [GR, Ro1, Ro2, Ro3, Kr, Oh].

Fact 5. θ has a perturbed Gaussian integral formula, with integration carried out over a space $6E$, consisting of 6 copies of the space of edges of a knot diagram D. See [BN2].

Conjecture 6. For any knot K, its genus $g(K)$ is bounded by the T_1-degree of θ: $g(K) < \lceil \deg_{T_1} \theta(K) \rceil$.

Conjecture 7. $\theta(K)$ has another perturbed Gaussian integral formula, with integration carried out over over the space $6H_1$, consisting of 6 copies of $H_1(\Sigma)$, where Σ is a Seifert surface for K.

Question 8.

Is there a direct quantum field theory derivation of θ? Perhaps using the ϵ-expansion (at constant k!) of Chern-Simons-Witten theory with gauge group $\mathfrak{g}^\epsilon_+ := \mathcal{D}(\mathfrak{b}, b, \epsilon\delta)$ with some Seifert-surface-dependent gauge fixing?

Expectation 9.

There are many further invariants like θ, given by Green function formulas and/or Gaussian integration formulas. One or two of them may be stronger than θ and as computable.

Dream 10.

These invariants can be explained by something less foreign than semisimple Lie algebras.

Dream 11.

θ will have something to say about ribbon knots.

Thank You!

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