Complexity:
from Turbulence to Accelerators to Poetry

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Dec. 15, 2023

Abstract

Though it may seem intuitive at times, the term 'complexity' is multifaceted, often encompassing various interacting aspects and components that follow local rules. This interaction leads to non-linearity, randomness, collective dynamics, hierarchy, and emergence. The phenomenological complexity found in large accelerators has recently been addressed by the Snowmass'21 Future Colliders Implementation Task Force (ITF). In this presentation, we will provide a concise overview of the mathematical constructs employed to assess hierarchical complexity, summarize the key findings from the ITF analysis, and offer a few examples demonstrating how this approach can be applied to analyze certain literary classics.

Part I:

Complexity

What is complexity?

- Something that we immediately recognize when we see it, but very hard to define quantitatively
- S. Lloyd, "Measures of complexity: a non-exhaustive list" – 40 different definitions
- Can be roughly divided into two categories:
  - computational/descriptive complexities
  - effective/physical or structural complexities

Computational and descriptive complexities

- Prototype – the *Kolmogorov complexity:* the length of the shortest description (in a given language) of the object of interest

- Examples:
  - Number of gates (in a predetermined basis) needed to create a given state from a reference one
  - Length of an instruction required by file compressing program to restore image

Descriptive Complexity

- The more random – the more complex:

Paris japonica - 150 billion base pairs in DNA

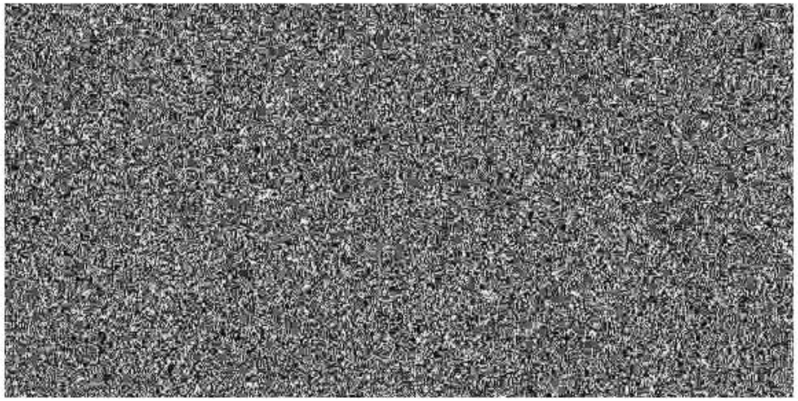
≫

Homo sapiens - 3.1 billion base pairs in DNA

… Kolmogorov complexity does not work for us…

Descriptive Complexity

- The more random – the more complex:



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White noise
970 x 485 pixels, gray scale, 253 Kb

Vermeer "View of Delft"
750 x 624 pixels, colored, 234 Kb

Structural Complexity: Hierarchy and Patterns

Multi-scale structural complexity of natural patterns **arXiv:2003.04632**

Andrey A. Bagrov,[1,2,*] Ilia A. Iakovlev,[2,†] Mikhail I. Katsnelson,[3,2,‡] and Vladimir V. Mazurenko[2]

PNAS (2020), 117 (48) 30241-30251

The idea (from holographic complexity and common sense):
Complexity is dissimilarity at various scales

Let $f(x)$ be a multidimensional pattern

$f_\Lambda(x)$ its coarse-grained version (Kadanoff decimation, convolution with Gaussian window functions,…)

Complexity is related to distances between $f_\Lambda(x)$ and $f_{\Lambda+d\Lambda}(x)$

$$\langle f(x)|g(x)\rangle = \int_D dx f(x)g(x)$$

$$\Delta_\Lambda = |\langle f_\Lambda(x)|f_{\Lambda+d\Lambda}(x)\rangle - \frac{1}{2}\left(\langle f_\Lambda(x)|f_\Lambda(x)\rangle + \langle f_{\Lambda+d\Lambda}(x)|f_{\Lambda+d\Lambda}(x)\rangle\right)| = \frac{1}{2}|\langle f_{\Lambda+d\Lambda}(x) - f_\Lambda(x)|f_{\Lambda+d\Lambda}(x) - f_\Lambda(x)\rangle|,$$

$$\mathcal{C} = \sum_\Lambda \frac{1}{d\Lambda}\Delta_\Lambda \to \int |\langle \frac{\partial f}{d\Lambda}|\frac{\partial f}{d\Lambda}\rangle| d\Lambda, \text{ as } d\Lambda \to 0$$

Structural Complexity: An example

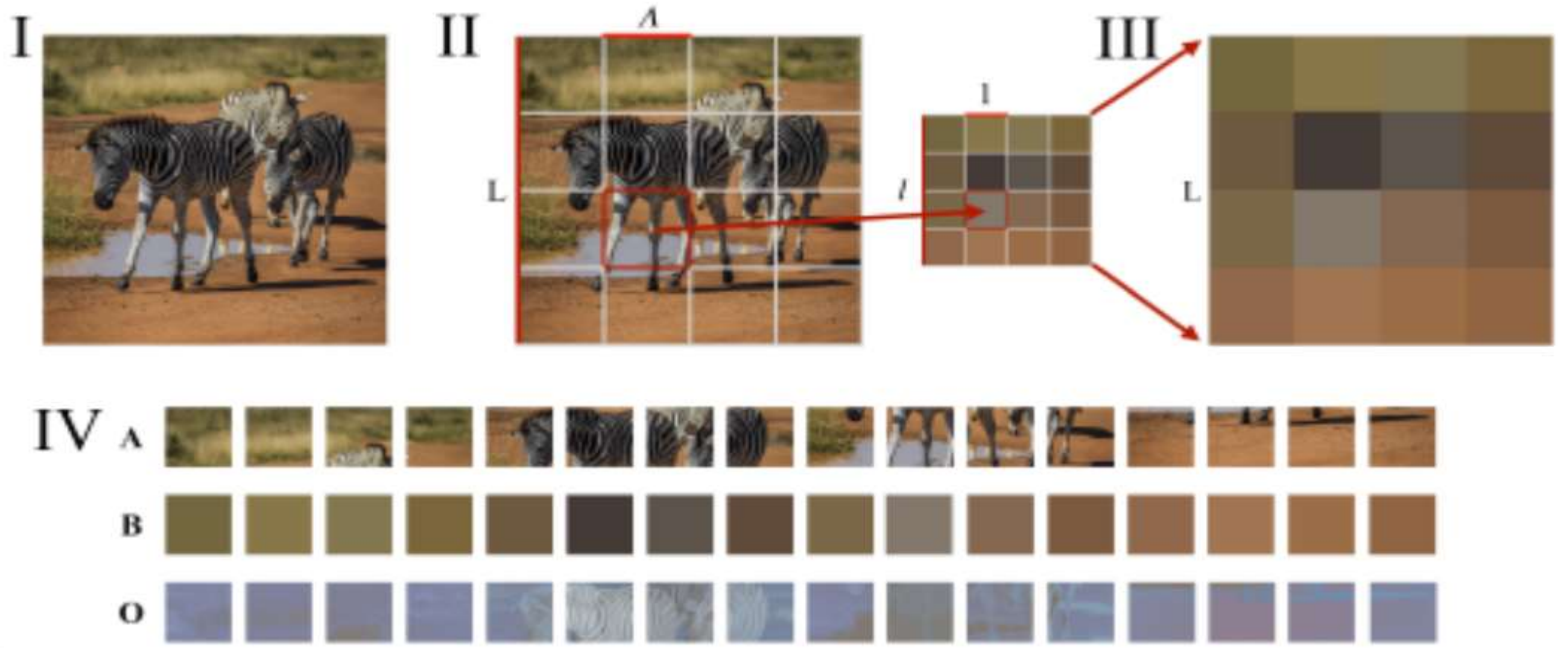


FIG. 1. Schematic representation of the idea behind the proposed method. A photo of $L \times L$ pixels (panel I) taken from www.pexels.com is divided into blocks of $\Lambda \times \Lambda$ pixels (panel II). A renormalized photo of $l \times l$ pixels is plotted, where $l = L/\Lambda$ (l=4 in this example). The renormalized photo is rescaled up to initial photo size (panel III). Vectors **A** and **B** are constructed from blocks of the initial and the renormalized images respectively (panel IV). The scalar product of these vectors is used to define overlap O. For illustrative purposes, pixelwise products of **A**- and **B**-blocks are shown as vector **O**.

Example #1: Ink drop in a water

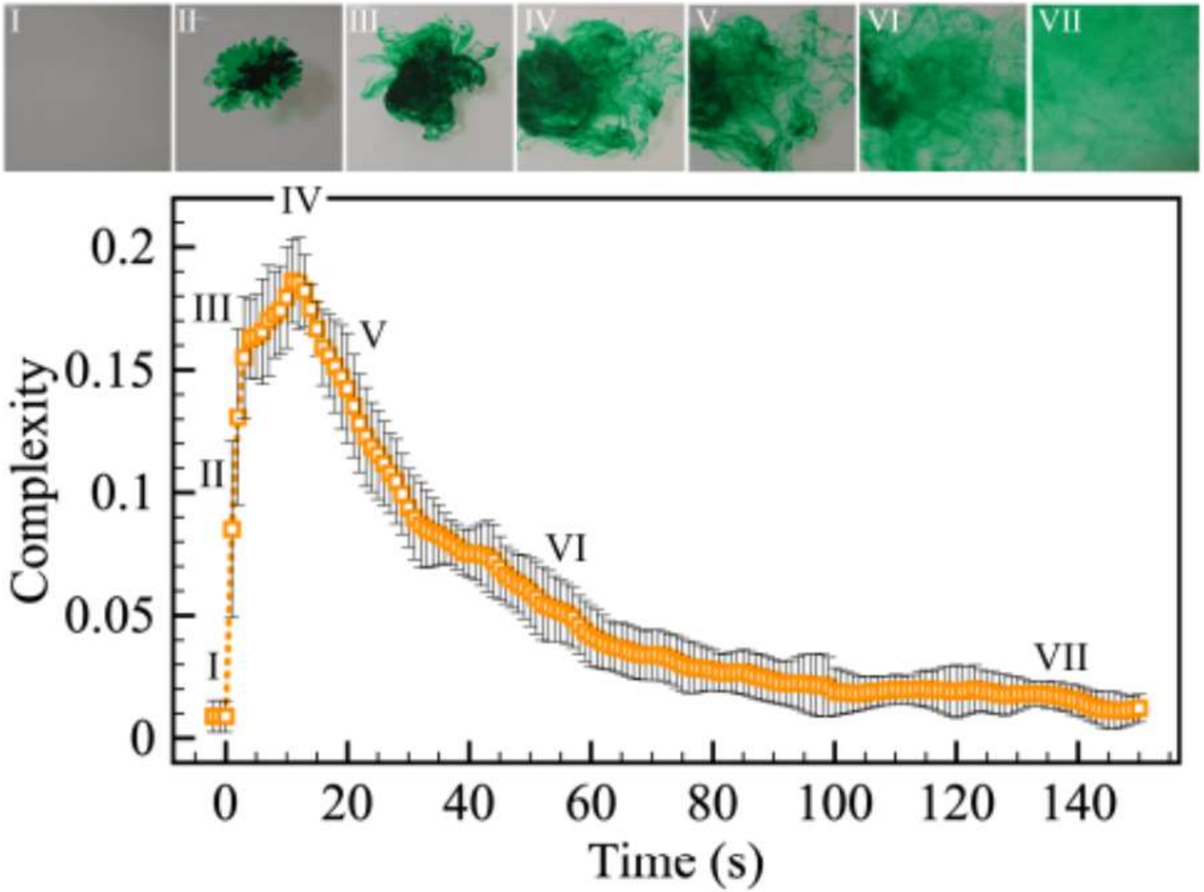
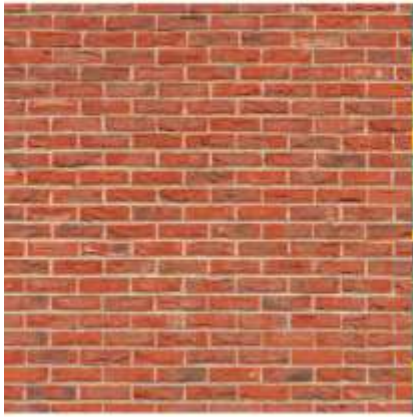


FIG. 7. The evolution of the complexity during the process of dissolving a food dye drop of 0.3 ml in water at 31°C.

Example #2: Art Objects (and Walls)



$C = 0.1076$

$C = 0.2010$

$C = 0.2147$

$C = 0.2765$

$C = 0.4557$

$C = 0.4581$

$C = 0.4975$

$C = 0.5552$

Part II:

Complexity of Accelerators

Accelerator Complexity – What's That? (1)

- It is generally accepted that modern accelerators are very sophisticated systems and that, e.g., "…*The LHC is the most complex scientific instrument of our time*".
- Possible aspects to look at may include:

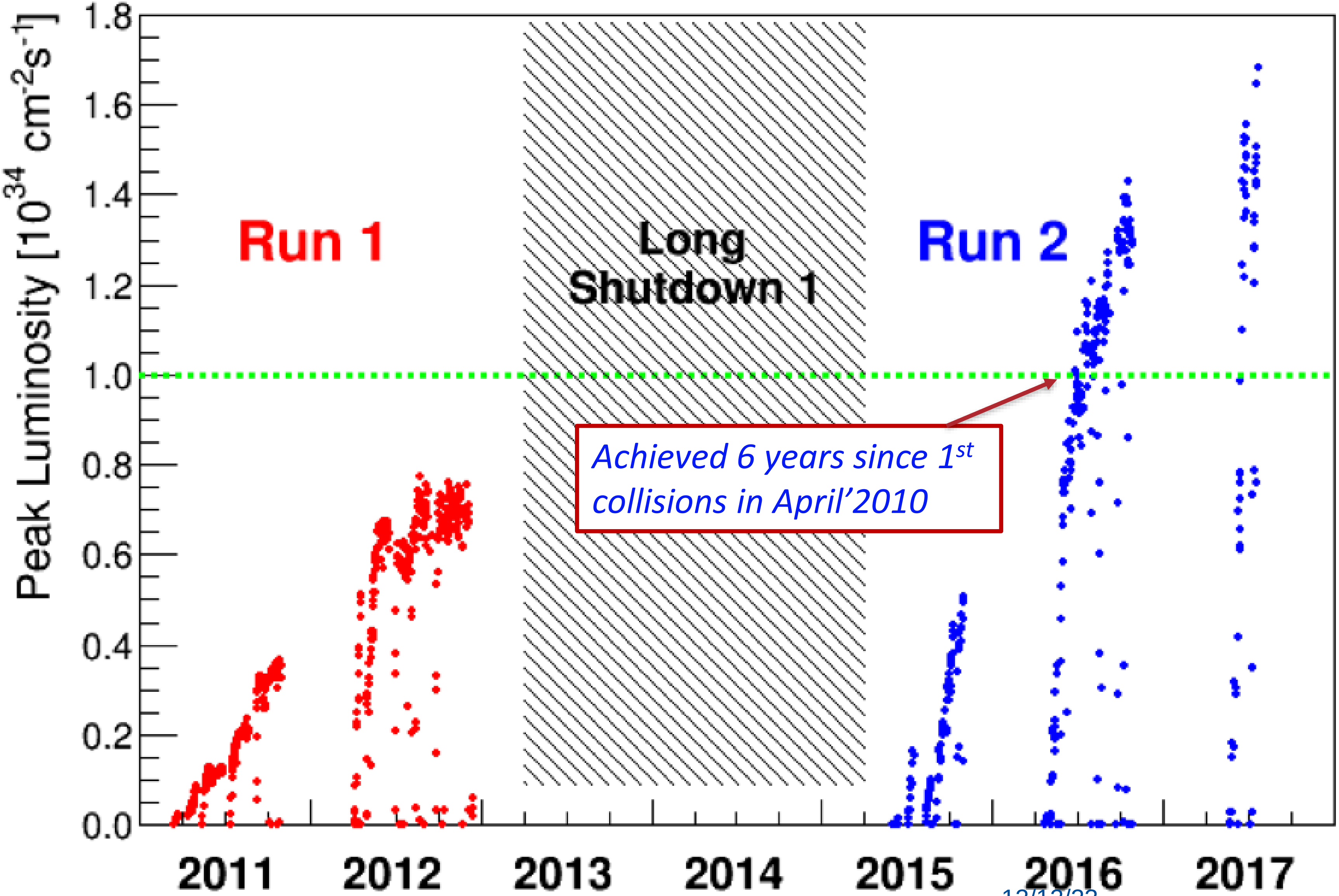
Complexity I : to design and build (many dissimilar systems, of various scales : # elements, # of systems, level of each system – "standard/off-shelf, special, unique")

Complexity II : to reach energy ="make it work" (reliability)

Complexity III : to reach performance ("luminosity")

Presumably, all three are related…

LHC: Design Lumi in July 2016



Facts about Accelerators (1)

Collider	Time to Reach Design Peak L	Record L / Design L
LEP-I	5 years	×2
SLC	Not achieved (9 years)	×0.5
LEP-II	0.3 years	×3
PEP-II	1.5 years	×4
KEK-B	3.5 years	×2
BEPC-II	7.5 years	×1.0
DAFNE	Not achieved (9 years)	×0.9
Super-KEK-B	Not yet achieved (4 years)	×0.05*
TEV-Ib	1.5 years	×1.5
HERA-I	8 years	×1
RHIC-pp	10 years**	×1.2*
TEV-II	5 years	×2.1
HERA-II	5 years	×1
LHC	6 years	×2.1*

Table 12. Time required to reach design peak luminosity for several recent lepton and hadron particle colliders. The last column indicates maximum achieved luminosity w.r.t. to the design luminosity. (* colliders still in high-luminosity operation; ** RHIC operation in pp collider mode was intermittent with heavy ions collisions runs.)

T.Roser et al, "ITF Report", JINST 18 P05018 (2023)

"CPT Theorem for Accelerators"

$$C \times P = T$$

C = Complexity of the machine

P = Performance (or Challenge)

$= \log_e (\textit{Lumi Increase Ratio})$

T = Time to reach P

i.e., $L(T)=L(0) \times \exp(T/C)$

V.Shiltsev, Modern Physics Letters A
Vol. 26, No. 11 (2011) 761–772

"CPT Theorem" : Phenomenological *"Complexity"*

more like "difficulty" - ?

$$L(t_0 + T) = L(t_0) \times e^{T/C}$$

$$C \cdot P = T$$

Table 1. "Complexities" of colliding beam facilities.	C, years	Interval
SLC e^+e^-	1.6 ± 0.1	1989–1997
Tevatron Run II p–$\bar{p}$	2.0 ± 0.2	2002–2007
RHIC p–p	2.2 ± 0.3	2000–2004
HERA p–e	2.8 ± 0.4	1992–2005
SppS p–$\bar{p}$	3.3 ± 0.2	1982–1990
LEP e^+e^-	3.3 ± 0.3	1989–1995
ISR p–p	3.7 ± 0.3	1972–1982
CESR e^+e^-	4.4 ± 0.4	1984–1997

ON PERFORMANCE OF HIGH ENERGY PARTICLE COLLIDERS AND OTHER COMPLEX SCIENTIFIC SYSTEMS

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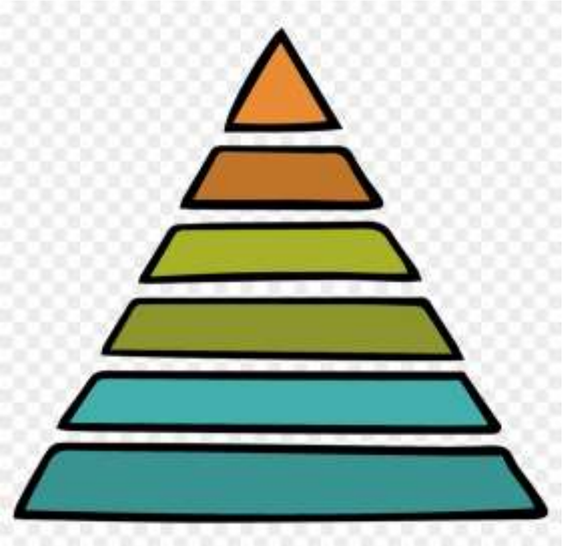
Modern Physics Letters A
Vol. 26, No. 11 (2011) 761–772

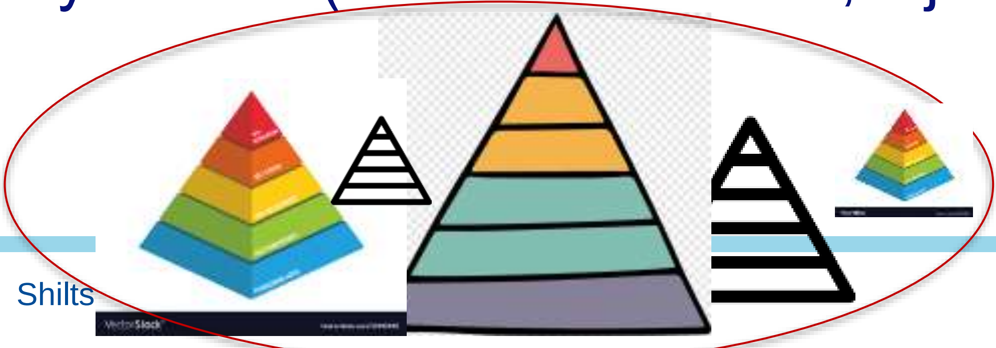
LHC Lx100 in 2010-2018 (8 yrs) → Complexity=8/4.6=1.74

Accelerator "Complexity to Design and Build" : Let's Follow the "*Structural Complexity*" Approach

- Complexity is about
  - Dissimilarity
    - Magnets, RF, plasma, cooling, drivers, FF, etc
  - And Hierarchy:
    - Eg LHC 1 ring
      O(10) sectors
      O(100) cells
      O(1000) main magnets
      O(10^4) aux magnets,
      O(10^5) control channels



- Other "Pyramids" (RF linacs/cavities, injectors, etc)



Snowmass'21 *Future Colliders Implementation Task Force* has Looked into *Complexity of Future Colliders*

$$\mathbf{C} = \sum_{\text{subsystems}} (C_i + \Delta_i)$$

T.Roser et al, "ITF Report", JINST 18 P05018 (2023)

where individual subsystem complexity is

$$C_i \simeq \log_{10}(\text{Number of elements in } i\text{-th subsystem})$$

Fermilab

More on Hierarchy and Complexity

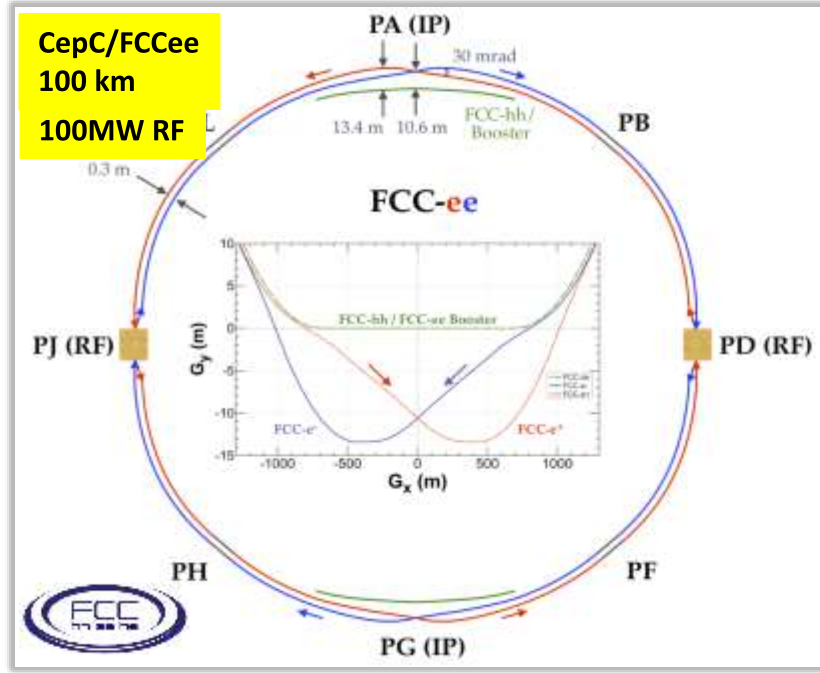
- Complexity is **~ Log(# elements):**
  - Eg if complexity of 1 element is 1

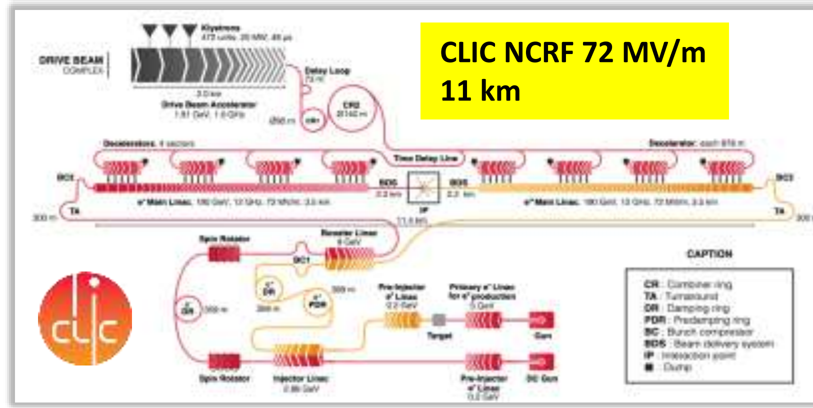
complexity of 1	element is	1
complexity of 10	elements is	2
complexity of 100	elements is	3
complexity of 1000	elements is	4
complexity of 10^4	elements is	5
complexity of 10^5	elements is	6

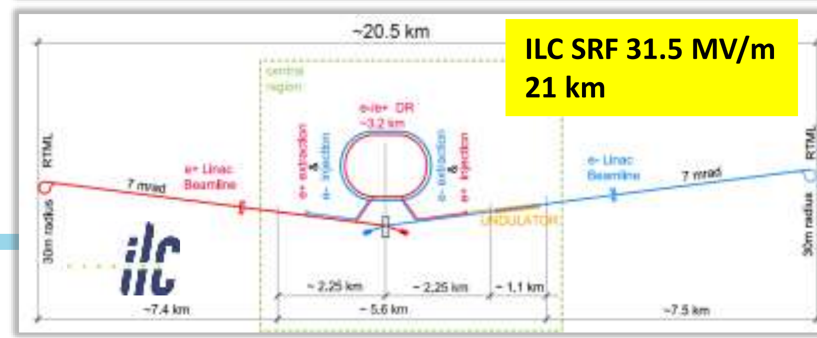
- **Unfamiliarity** is another factor
  – Advanced vs Traditional - add a unit (ie 10 SC 8 T ~ 100 NC) or more
  – Beyond state-of-art vs advanced – add a unit (16T ~10x 8 T) or more

Future Collider Proposals: 8 Higgs/EW factories

Name	Details
CepC	e+e-, $\sqrt{s} = 0.24$ TeV, L= 3.0 $\times 10^{34}$
CLIC (Higgs factory)	e+e-, $\sqrt{s} = 0.38$ TeV, L= 1.5 $\times 10^{34}$
ERL ee collider	e+e-, $\sqrt{s} = 0.24$ TeV, L= 73 $\times 10^{34}$
FCC-ee	e+e-, $\sqrt{s} = 0.24$ TeV, L= 17 $\times 10^{34}$
gamma gamma	X-ray FEL-based $\gamma\gamma$ collider
ILC (Higgs factory)	e+e-, $\sqrt{s} = 0.25$ TeV, L= 1.4 $\times 10^{34}$
LHeC	ep, $\sqrt{s} = 1.3$ TeV, L= 0.1 $\times 10^{34}$
MC (Higgs factory)	$\mu\mu$, $\sqrt{s} = 0.13$ TeV, L= 0.01 $\times 10^{34}$

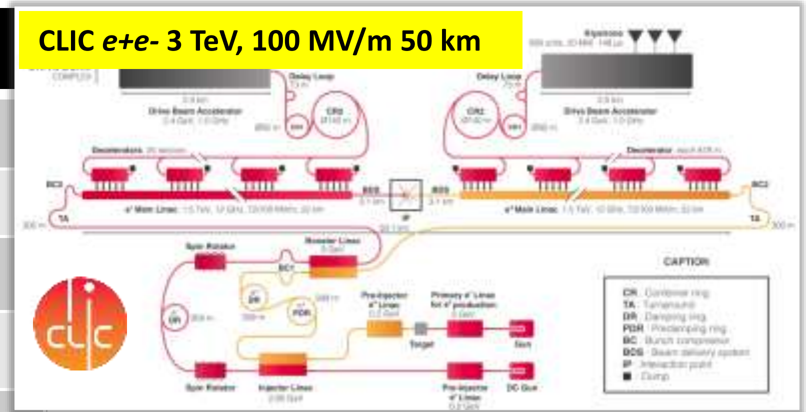


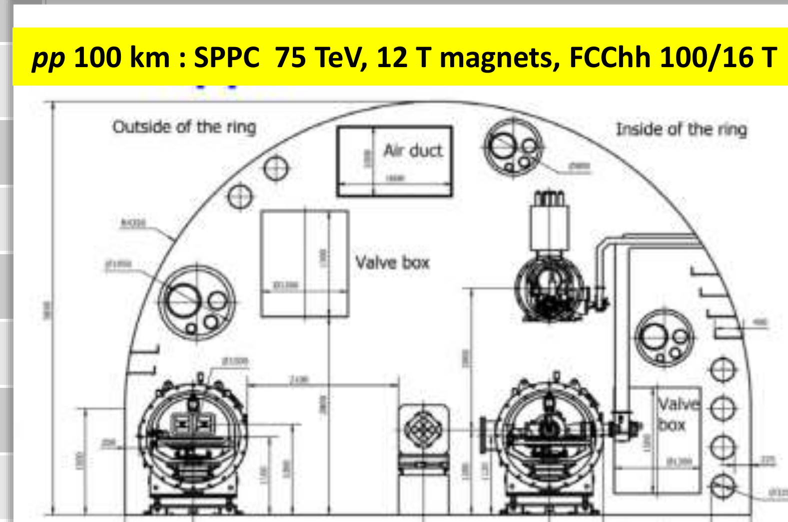




17 (!) High Energy Collider Concepts/Proposals

Name	Details
Cryo-Cooled Copper linac	e+e-, $\sqrt{s} = 2$ TeV, L= 4.5 $\times 10^{34}$
High Energy CLIC	e+e-, $\sqrt{s} = 1.5 - 3$ TeV, L= 5.9 $\times 10^{34}$
High Energy ILC	e+e-, $\sqrt{s} = 1 - 3$ TeV
FCC-hh	pp, $\sqrt{s} = 100$ TeV, L= 30 $\times 10^{34}$
SPPC	pp, $\sqrt{s} = 75/150$ TeV, L= 10 $\times 10^{34}$
Collider-in-Sea	pp, $\sqrt{s} = 500$ TeV, L= 50 $\times 10^{34}$
LHeC	ep, $\sqrt{s} = 1.3$ TeV, L= 1 $\times 10^{34}$
FCC-eh	ep, $\sqrt{s} = 3.5$ TeV, L= 1 $\times 10^{34}$
CEPC-SPPpC-eh	ep, $\sqrt{s} = 6$ TeV, L= 4.5 $\times 10^{33}$
VHE-ep	ep, $\sqrt{s} = 9$ TeV
MC – Proton Driver 1	$\mu\mu$, $\sqrt{s} = 1.5$ TeV, L= 1 $\times 10^{34}$
MC – Proton Driver 2	$\mu\mu$, $\sqrt{s} = 3$ TeV, L= 2 $\times 10^{34}$
MC – Proton Driver 3	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, L= 20 $\times 10^{34}$
MC – Positron Driver	$\mu\mu$, $\sqrt{s} = 10 - 14$ TeV, L= 20 $\times 10^{34}$
LWFA-LC (e+e- and $\gamma\gamma$)	Laser driven; e+e-, $\sqrt{s} = 1 - 30$ TeV
PWFA-LC (e+e- and $\gamma\gamma$)	Beam driven; e+e-, $\sqrt{s} = 1 - 30$ TeV
SWFA-LC	Structure wakefields; e+e-, $\sqrt{s} = 1 - 30$ TeV





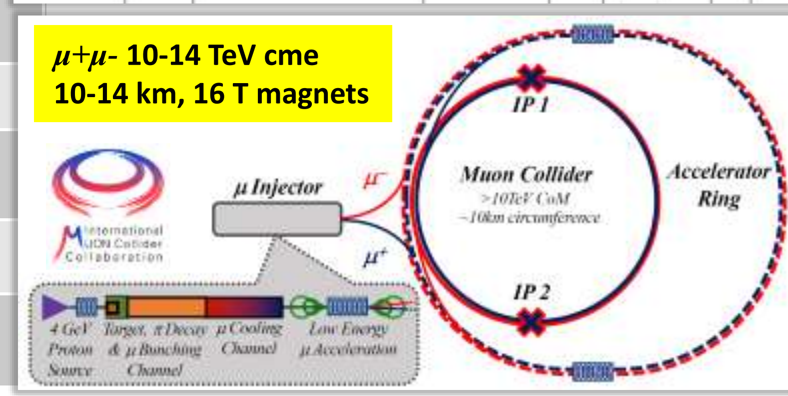


Table of Complexities (for illustration)

	ΔC of Magnets	*ΔC* of RF cav	*ΔC* of Injectors	*ΔC* of cool/prod	*ΔC* of FF	*C* Sum
LHC	4.5	1	2.5			**8**
Tevatron	4	1	2.5	2		**9.5**
ILC-0.25	1	5	2	1 (e+)	1	**10**
CLIC-0.38	2	5	2	1.5 (drive)	1	**11**
C^3-0.25	1.5	4.5	2	1 (e+)	1	**10**
FCCee	4	3	3-3.5			**10-10.5**
ILC-3	2	6	2	1 (e+)	1.5	**12.5**
CLIC-3	3	6	2	2 (drive)	1.5	**14.5**
MC-3	2.5-3	3	2.5-3	2.5		**10-11**
MC-10	3-3.5	3-3.5	3	2.5		**11.5-12.5**
FCChh	5-6	2	4			**11-12**
L/PWA-1	3	4-5	2	2 (drive)	1.5	**13.5-14.5**

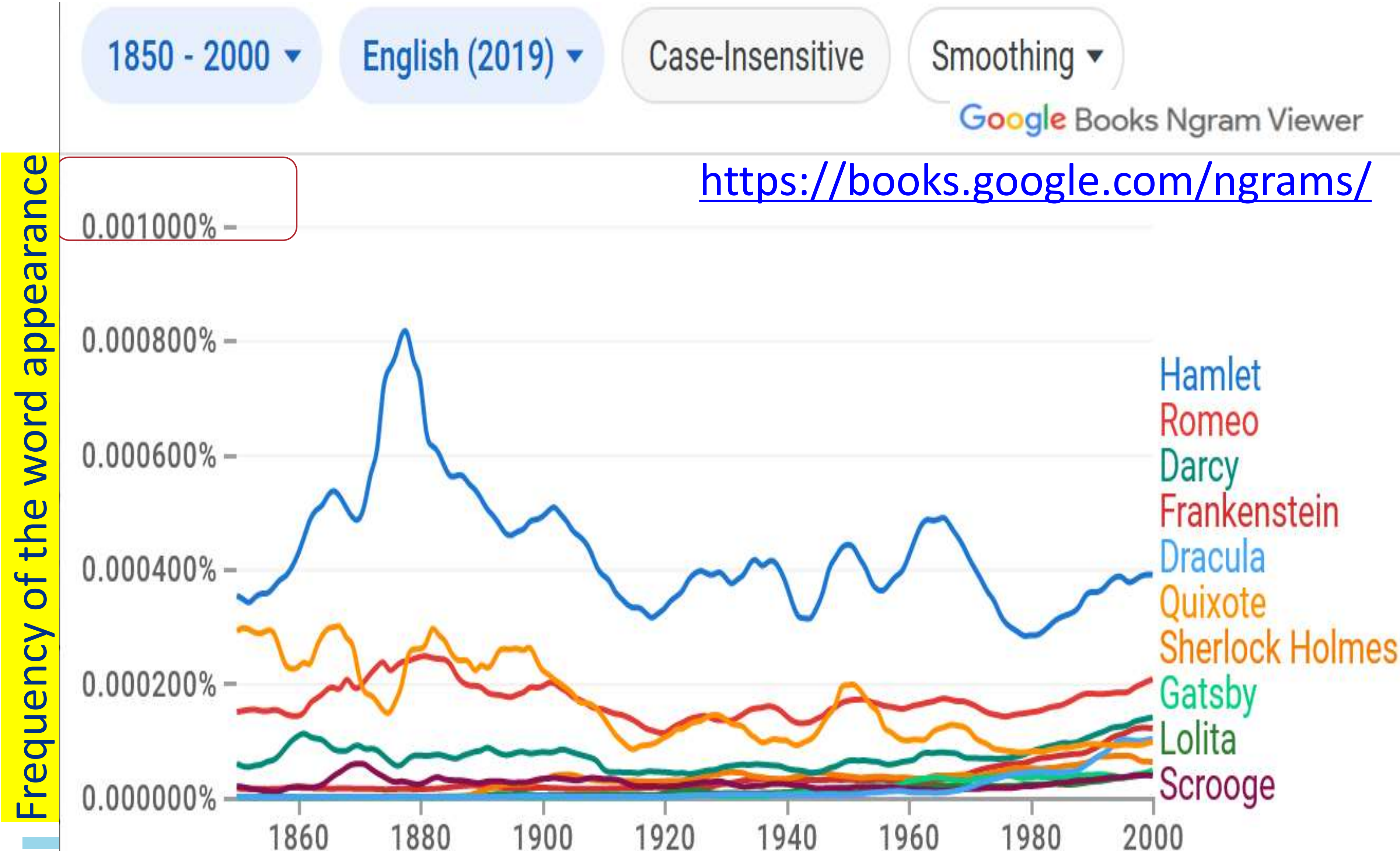
ITF Report : Complexity Table

Proposal Name	Complexity
FCC-ee (0.24 TeV)	I
CEPC (0.24 TeV)	I
ILC (0.25 TeV)	I
CLIC (0.38 TeV)	II
CCC (0.25 TeV)	I
CERC (0.24 TeV)	II
ReLiC (0.24 TeV)	II
ERLC (0.24 TeV)	II
XCC (0.125 TeV)	II
MC (0.13 TeV)	I
ILC (3 TeV)	II
CLIC (3 TeV)	III
CCC (3 TeV)	II
ReLiC (3 TeV)	III
MC (3 TeV)	II
LWFA (3 TeV)	II
PWFA (3 TeV)	II
SWFA (3 TeV)	II
MC (14 TeV)	III
LWFA (15 TeV)	III
PWFA (15 TeV)	III
SWFA (15 TeV)	III
FCC-hh (100 TeV)	II
SPPC (125 TeV)	II

T.Roser et al, "ITF Report", JINST 18 P05018 (2023)

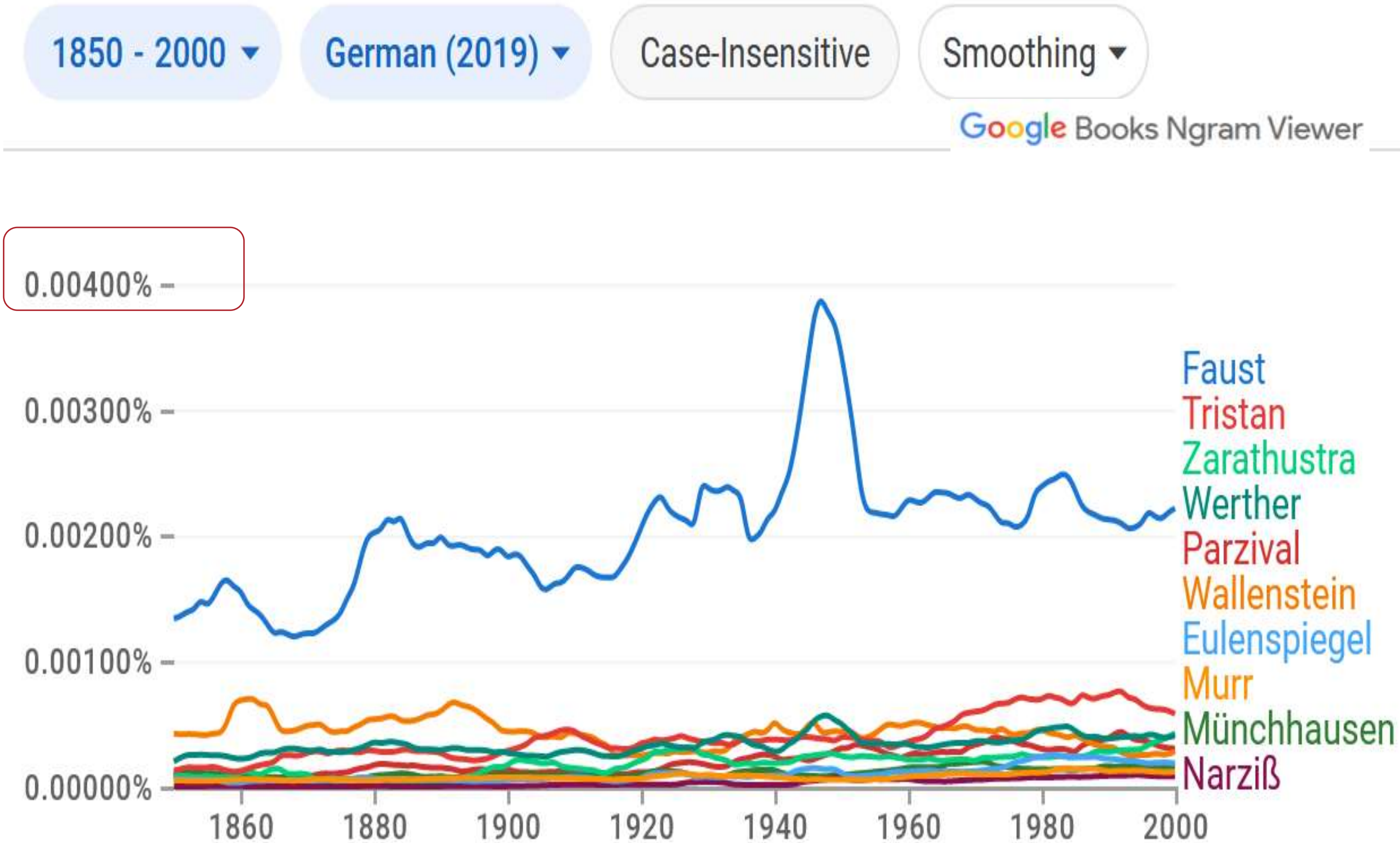
Part III:
(and attempt on)
Complexity of Literary Works (Poetry)

Top-10 Literature Heroes : in English



https://books.google.com/ngrams/

Top-10 Literature Heroes : in German



Top-10 Literature Heroes : in Russian

Onegin
Zhivago
Raskolnikov
Chichikov
Karenina
Chatsky
Pechorin
Woland
Bender
Melekhov

"Structural (Semantic) Complexity"

Eugene Onegin **Shakespeare's Sonnets**

Q#1 : what units to use?... Words?...too many

…Lines?... Do they carry semantic weight individually?

- Let's use Stanzas/Sonnets

411 **154**

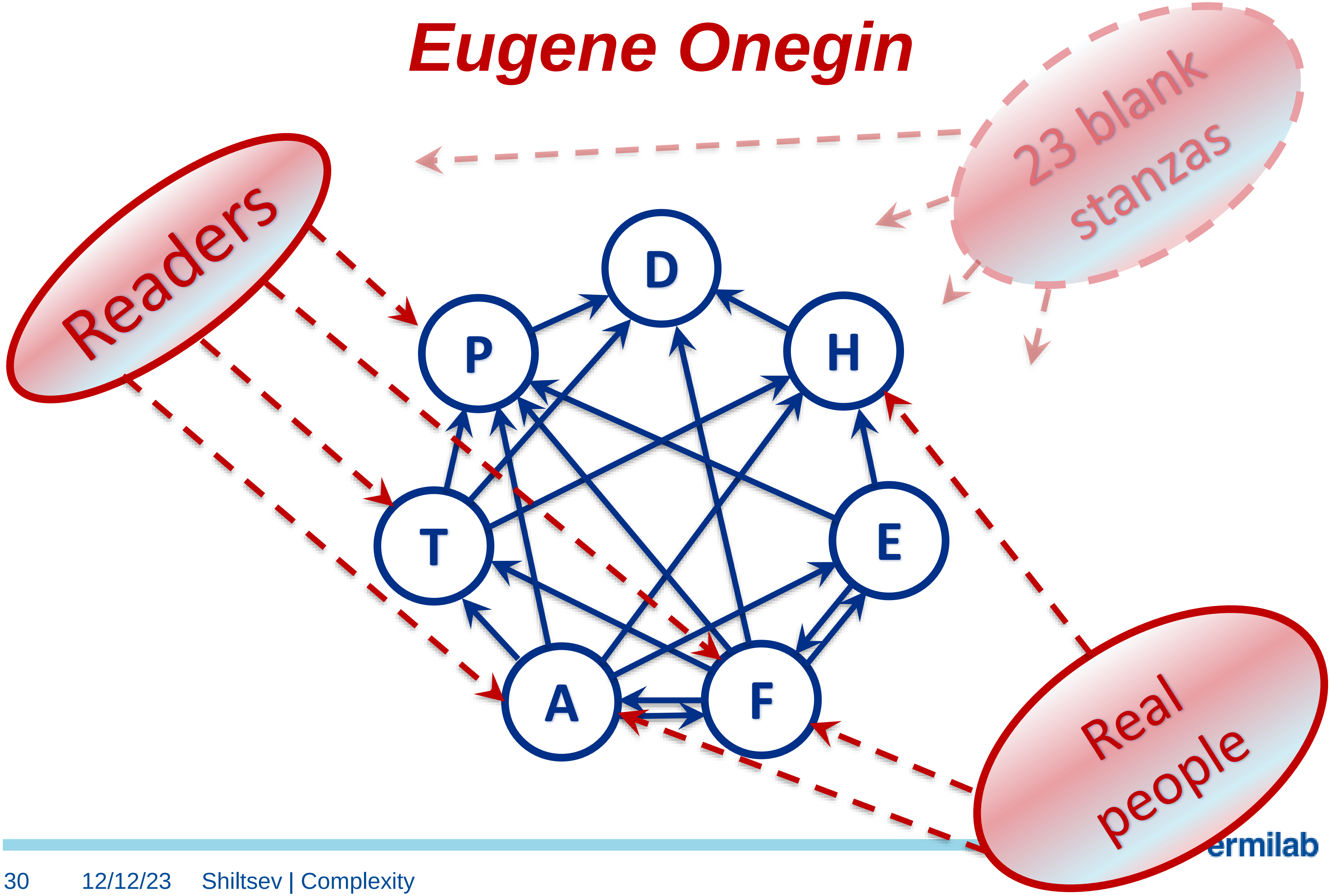
- Formally calculated complexity:

ln(411) = 6.02 **ln(154) = 5.04**

Q#2 : are these structures technically equally?...

Semantics Connections

Eugene Onegin



"Structural (Semantic) Complexity"

Eugene Onegin

Q#3 : semantic "tunes"

Story plot, heroes	**~156**
Lyrics, nature	**~93**
Author, Pushkin	**~49**
Russian life	**~33**
Ideas, philosophy	**~17**
History	**~6**
Devine, religious	**~4**

- Semantic complexity:

C = ln(156)+ln(93)+ln(49) + ln(33)+ln(17)+ln(6)+ +ln(4) = 51.6

…simplistic was ln(411) = 6.02

Shakespeare's Sonnets

Brevity of life	**~50**
Transients of beauty	**~50**
Transients of desire	**~50**

- Semantic complexity:

C = ln(52) + ln(51) + ln (51) = 11.8

…compare with simplistic estimate ln(154) = 5.04

Phenomenological Manifestation of the ***Complexity in Literature*** –

difficulty in translation

35 English Translations of *E.O.* (so far)

1. H.Spalding (1881)
2. B.Deutsch (1936, 1943, 1964)
3. O.Elton (1937)
4. D.Redin and G.Patrick (1937)
5. B.Simmons (1950)
6. W.Arndt (1963, 1992)
7. E.Kayden (1964)
8. V.Nabokov (1964, 1975)
9. C.Johnston (1977, 2003)
10. S.D.P.Clough (1988),
11. J.Falen (1990, 1995)
12. S.N.Kozlov (1994, 1998)
13. A.D.P. Briggs (1995, 2016)
14. M.Sharer (1996)
15. C.Cahill (1999)
16. R.Clarke (1999, 2011)
17. O.Emmet and S.Makurenkova (1999, 2009)
18. D.Hoffstaedter (1999)
19. G.R.Ledger (2001)
20. T.Beck (2004)
21. H.Hoyt (2008)
22. S.Michell (2008)
23. A.Kline (2009)
24. M.Hobson (2011, 2016)
25. D.M.Thomas (2011)
26. N.Portnoi (2016)
27. V.Balmont (2020)
28. C.Phillips-Walley (1883)*
29. W.Liberson (1975, 1987)*
30. A.Corre (1999)*
31. D.Litoshick (2001)*
32. E.Y.Bonver (2004)*
33. M.K.Stone (2005)**
34. J.H.Lowenfeld (2010)**
35. R.E.Tanner (2022)**

incomplete (28–32)

re-telling (33–35)

Thank you for your attention!

…special thanks to Frank for invitation

Some references

- CPT Theorem for Accelerators - V.Shiltsev, MPL A Vol. 26, No. 11, pp. 761-772 (2011)
- ITF Report – T.Roser et al., JINST 18 P05018 (2023)
- Structural complexity A.Bagrov et al, PNAS, v.117 (48) 30241-30251 (2020), (two slides borrowed from M.Katsnelson presentation at the RASA'21 Conference)
- V.Shiltsev, Semantic Polyphony of *E.O.*, Tyumen Univ. Humanitates, v.8, 99-130 (2022)
- Translations of *Eugene Onegin*: V.Nabokov, J.Falen, C.Johnston, V.Shiltsev (soon)

- Back up slides