"Evolutionary Informatics: Measuring the Cost of Success"

William A. Dembski

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Engineering & Computer Science

IEEE Computational Intelligence Society
MIMICKING NATURE FOR PROBLEM SOLVING

IEEE TRANSACTIONS ON EVOLUTIONARY COMPUTATION

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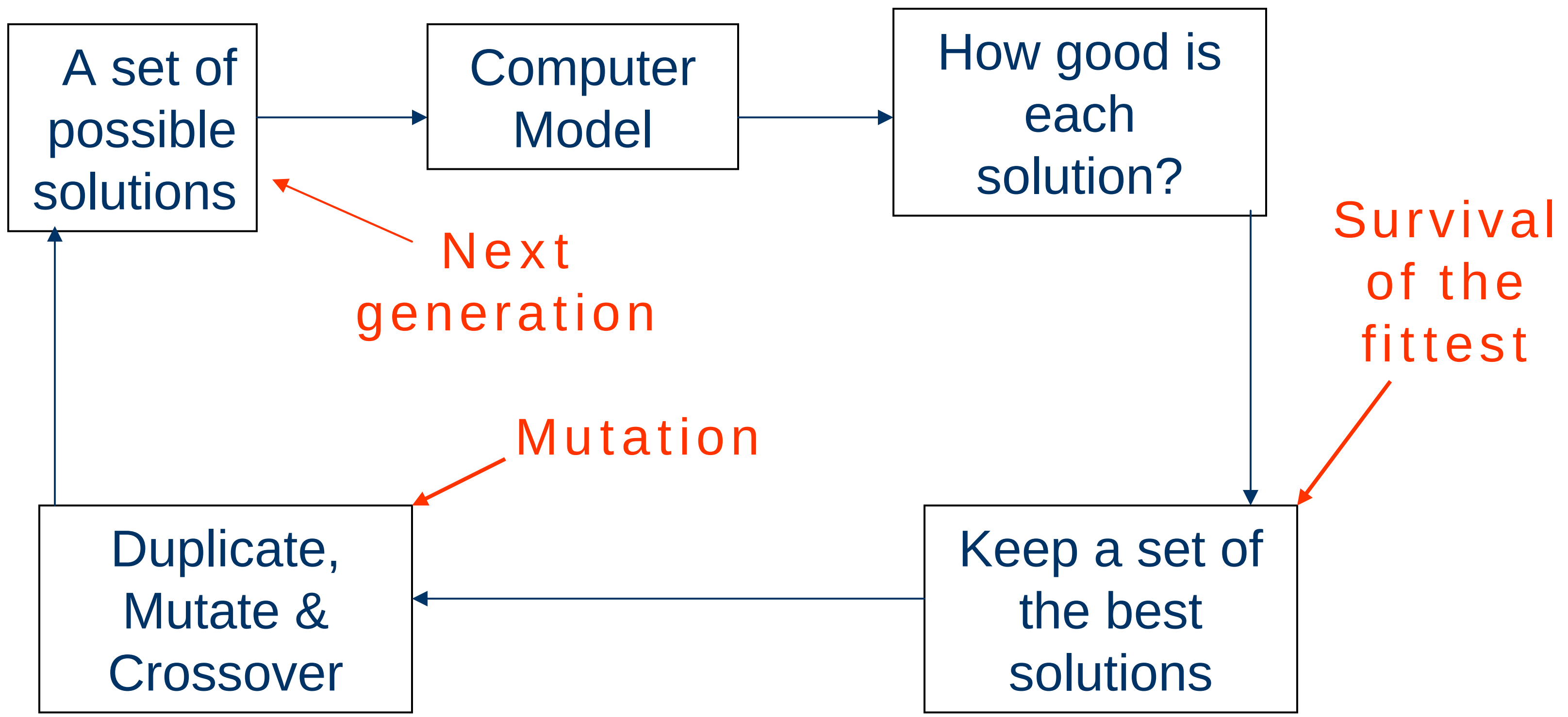
What is Evolutionary Search?

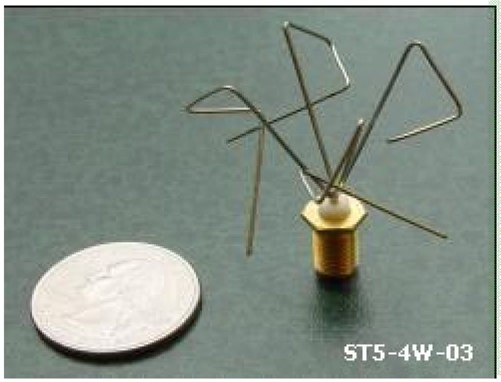
- Simulation of Darwinian Evolution on a Computer



Search in Engineering Design

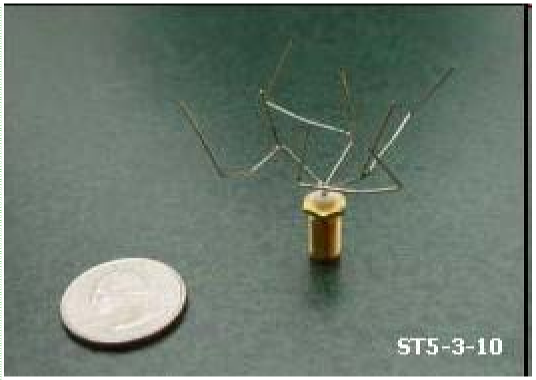
Can we do better? Engineers…

1. Create a parameterized model
2. Establish a measure design's fitness
3. Search the N-D parameter space



Designed by Evolutionary Search at NASA

http://ic.arc.nasa.gov/projects/esg/research/antenna.htm



No Free Lunch Theorem (1997)

With no knowledge of where the target is at and no knowledge about the fitness surface, one search performs, on average, as good as any another.

Widrow-Hoff Halley's method

Levenberg-Marquart

Evolutionary Strategies

Genetic Algorithms

Newton-Raphson

Random Search

Ant colony optimization

Search Strategies

Steepest Ascent

Householder's methods

Conjugate gradient

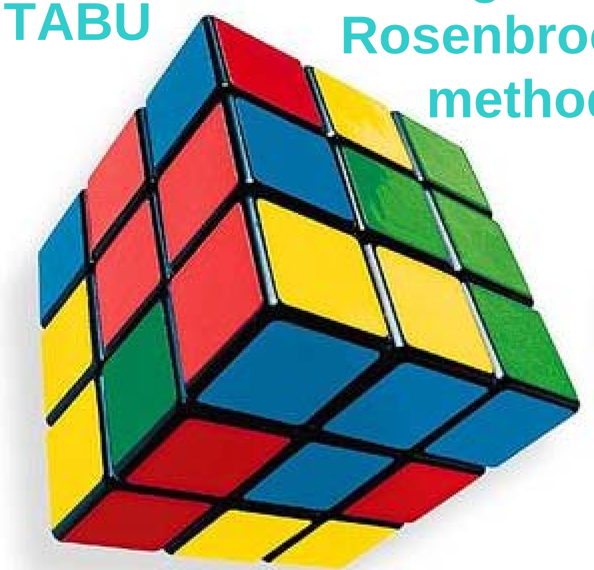
Cross-entropy method

Particle swarm optimization

Karmarkar's algorithm

TABU

Rosenbrock methods



Simulated annealing

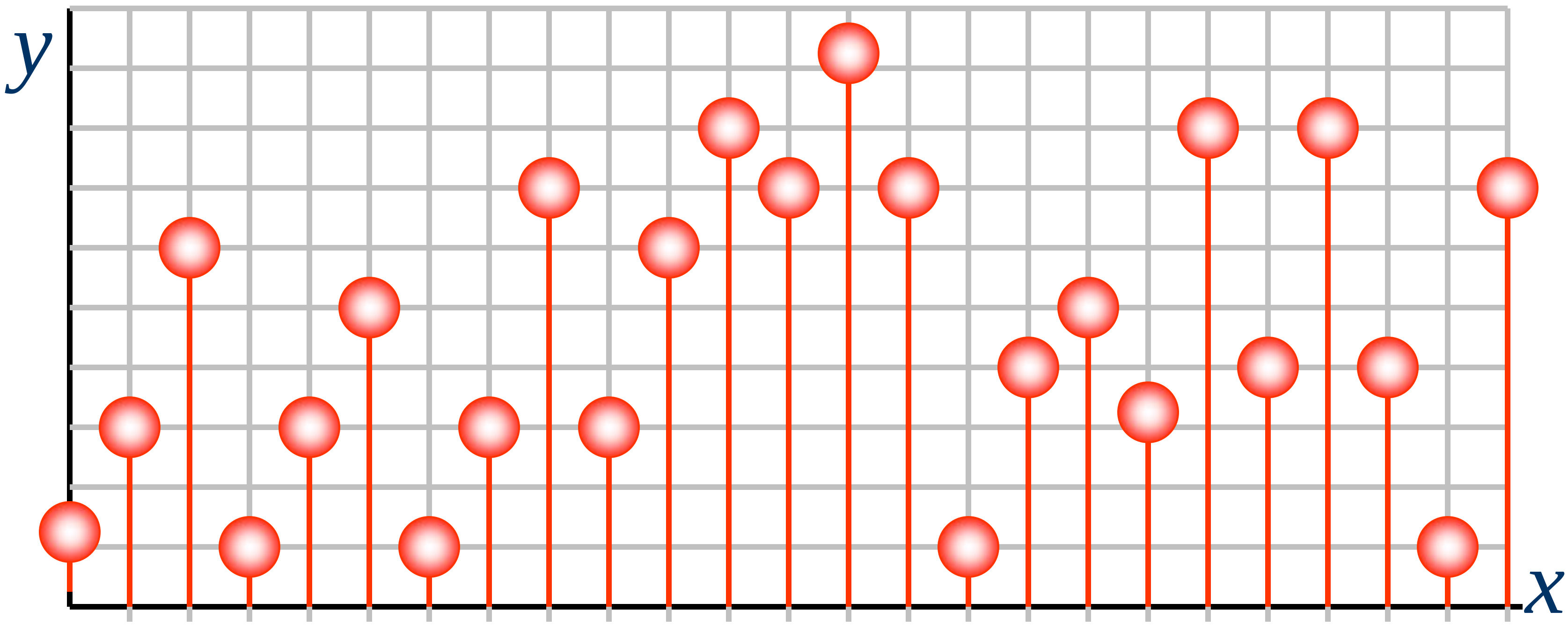
Stochastic gradient descent

PeregrinoGris/Búsqueda tabú

Karmarkar's algorithm Newton's method

No Free Lunch Theorem

Find the value of x that maximimizes the fitness, y.



Nothing is known about the fitness, y.

Cullen Schaffer (1994)

A Conservation Law for Generalization Performance

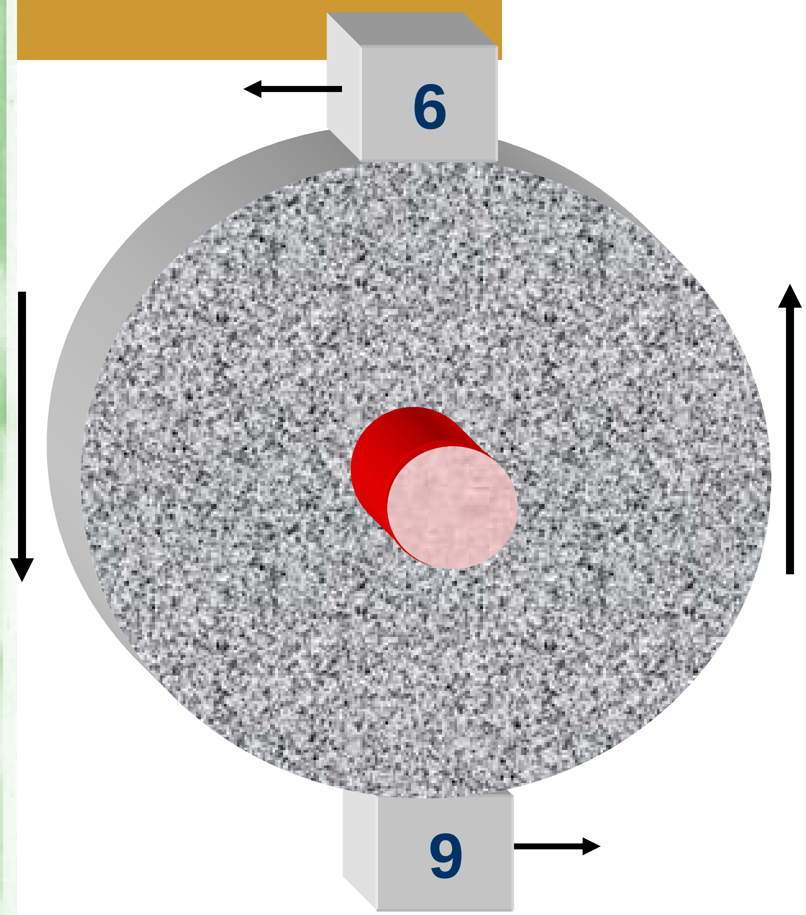
"About half of the people in the audience to which my work was directed told me that my result was completely obvious and common knowledge–which is perfectly fair. Of course, the other half argued just as strongly that the result wasn't true."

(Private Correspondence)

Can a computer program generate more information than it is given

?

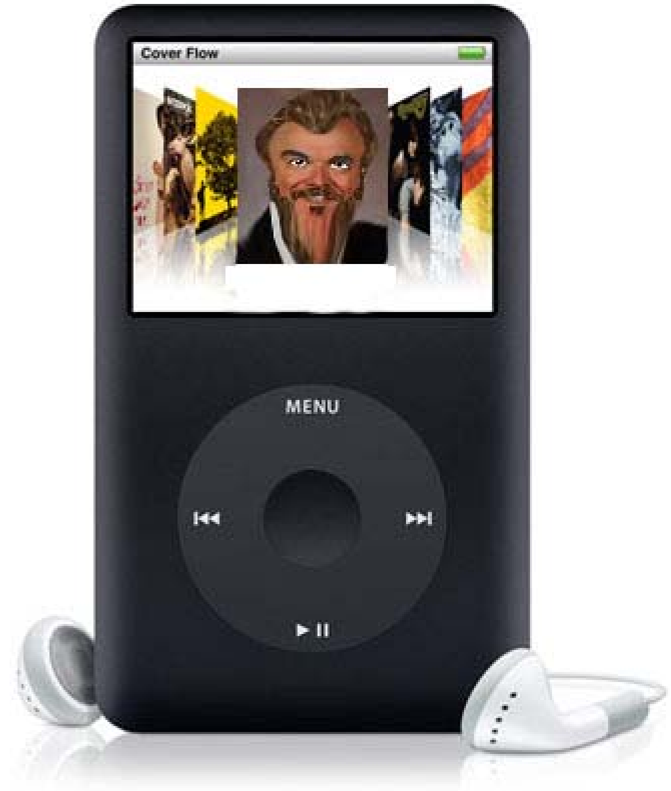
If a search algorithm does not obey the NFL theorem, it "is like a perpetual motion machine - conservation of generalization performance precludes it." Cullen Schaffer (1994)



3. Cullen Schaffer, 1994. "A conservation law for generalization performance,"in Proc. Eleventh International Conference on Machine Learning, H. Willian and W. Cohen, San Francisco: Morgan Kaufmann, pp.295-265.

Conservation of Information

A computer can create information no more than an iPod can create music



small probabilities

Impact: How Long a Phrase?

- IN THE BEGINNING ... EARTH ← Target

- JFD SDKA ASS SA ... KSLLS
- KASFSDA SASSF A ... JDASF
- J ASDFASD ASDFD ... ASFDG
- JASKLF SADFAS D ... ASSDF

.
.
.

- IN THE BEGINNING ... EARTH

← L →

Expected number

$$1/p = N^L$$

$$B = N^L \log_2 N^L$$

4.7549 bits per letter for 26 letters and a space

How Long a Phrase?

$$B = \frac{-\log p}{p}$$

Number of bits expected for a random search

$$p = N^{-L}$$

$$10^{100} \text{ bits} = N^L \log_2 N^L$$

For $N = 27$,

$L = 68$ characters

How Long a Phrase from the Universe?

Free punctuation:

"IN THE BEGINNING GOD CREATED THE HEAVEN AND THE EARTH. AND THE EARTH W…"

For $N = 27$,

$L = 68$ characters

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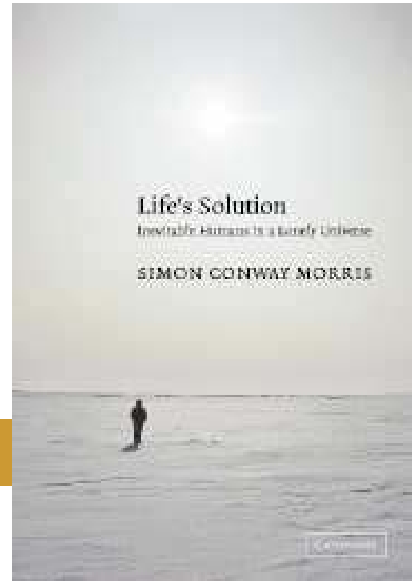
Objection!



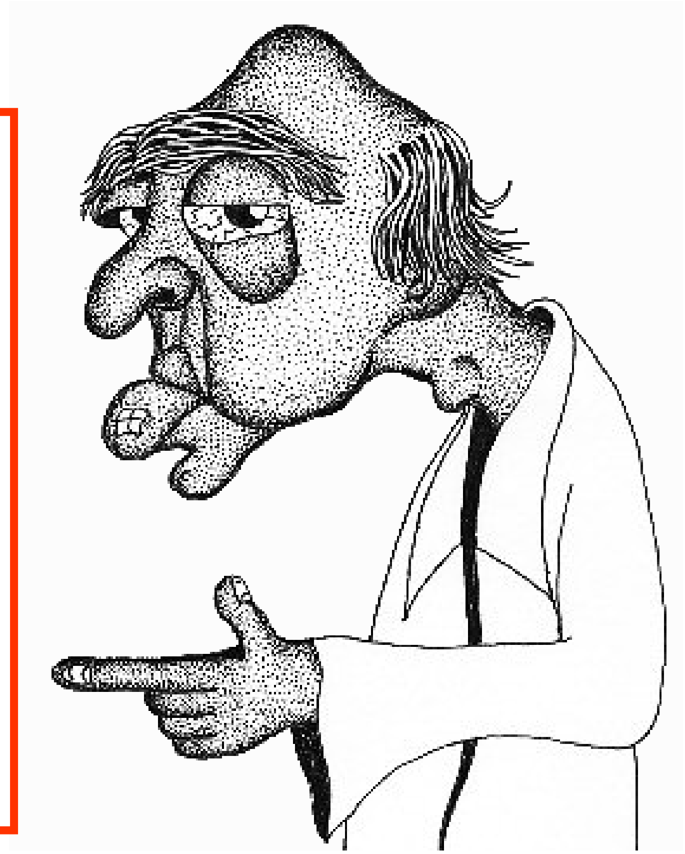
- Single Target
  - Functional Information
  - Spell Check
- Teleological
  - AVIDA, ev
  - implicit teleology
    - Guided by landscape
    - Simon Conway Morris, convergence

Simon Conway Morris, Life's Solution: Inevitable Humans in a Lonely Universe, Cambridge University Press (September 8, 2003).

How Long a Phrase from a Multiverse?

$$B = \frac{-\log p}{p}$$

10^{1000} universes gives a 766 letter search.



How Long a Phrase from a Multiverse?

$$B = \frac{-\log p}{p}$$

766 letters (Free Punctuation): 7 ½ Verses

IN THE BEGINNING GOD CREATED THE HEAVEN AND THE EARTH. AND THE EARTH WAS WITHOUT FORM, AND VOID; AND DARKNESS WAS UPON THE FACE OF THE DEEP. AND THE SPIRIT OF GOD MOVED UPON THE FACE OF THE WATERS. AND GOD SAID, LET THERE BE LIGHT: AND THERE WAS LIGHT. AND GOD SAW THE LIGHT, THAT IT WAS GOOD: AND GOD DIVIDED THE LIGHT FROM THE DARKNESS. AND AND GOD CALLED THE LIGHT DAY, AND THE DARKNESS HE CALLED NIGHT. AND THE EVENING AND THE MORNING WERE THE FIRST DAY. AND GOD SAID, LET THERE BE A FIRMAMENT IN THE MIDST OF THE WATERS, AND LET IT DIVIDE THE WATERS FROM THE WATERS. AND GOD MADE THE FIRMAMENT, AND DIVIDED THE WATERS WHICH WERE UNDER THE FIRMAMENT FROM THE WATERS WHICH WERE ABOVE THE FIRMAMENT: AND IT WAS SO. AND GOD CALLED THE FIRMAMENT HEAVEN. AND THE EVENING AND THE MORNI...

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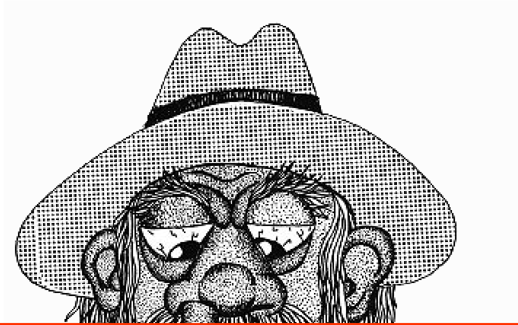
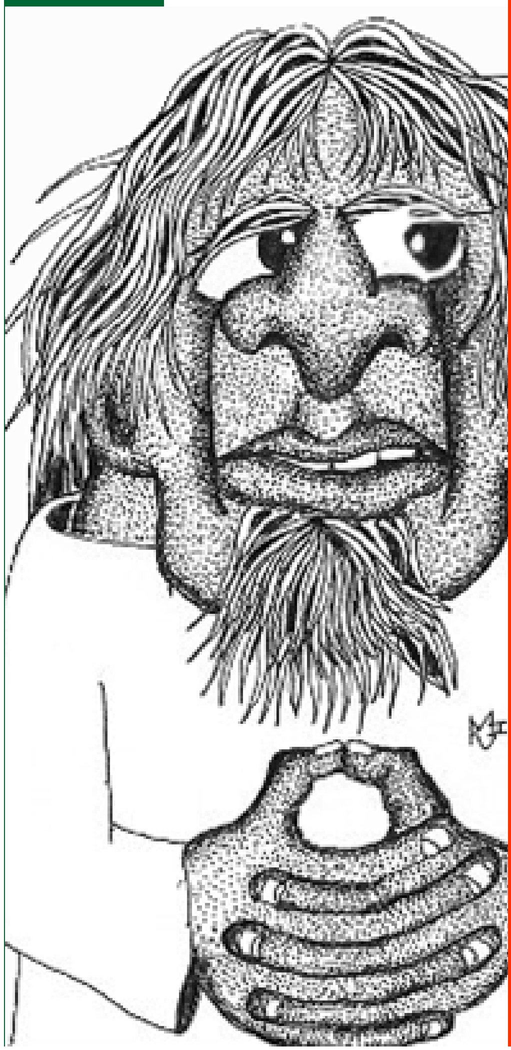
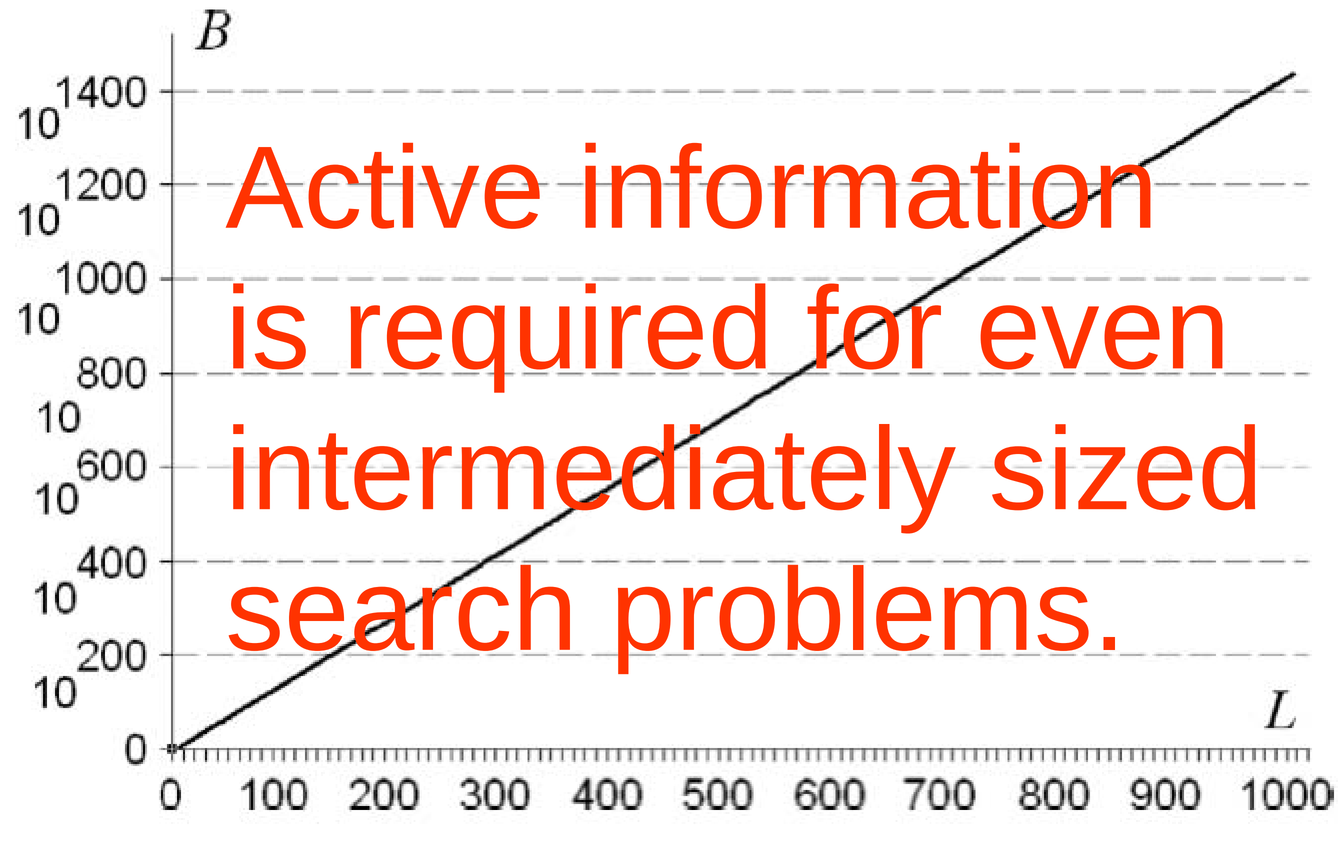




Active information is required for even intermediately sized search problems.



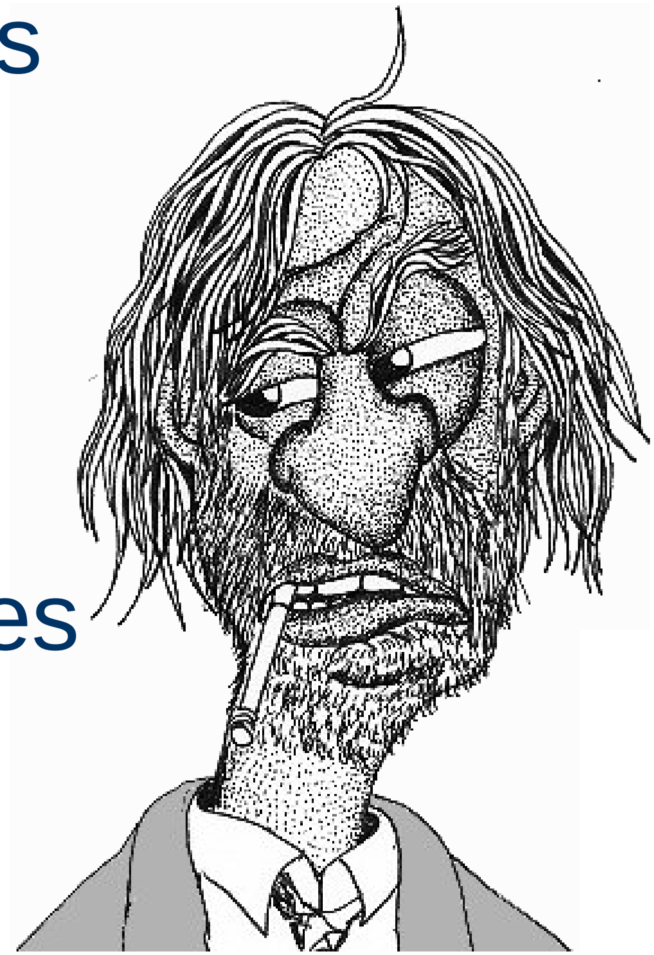
For $N = 27$, the number of bits B expected for a search of a phrase of length L. $L \to \infty$, we have the asymptote $\log(B) \to L \log N$. This explains the linear appearance of this plot.

Does Moore's Law Help?

Computer today searches for a target of B =10000 bits in a year.

Double the speed.

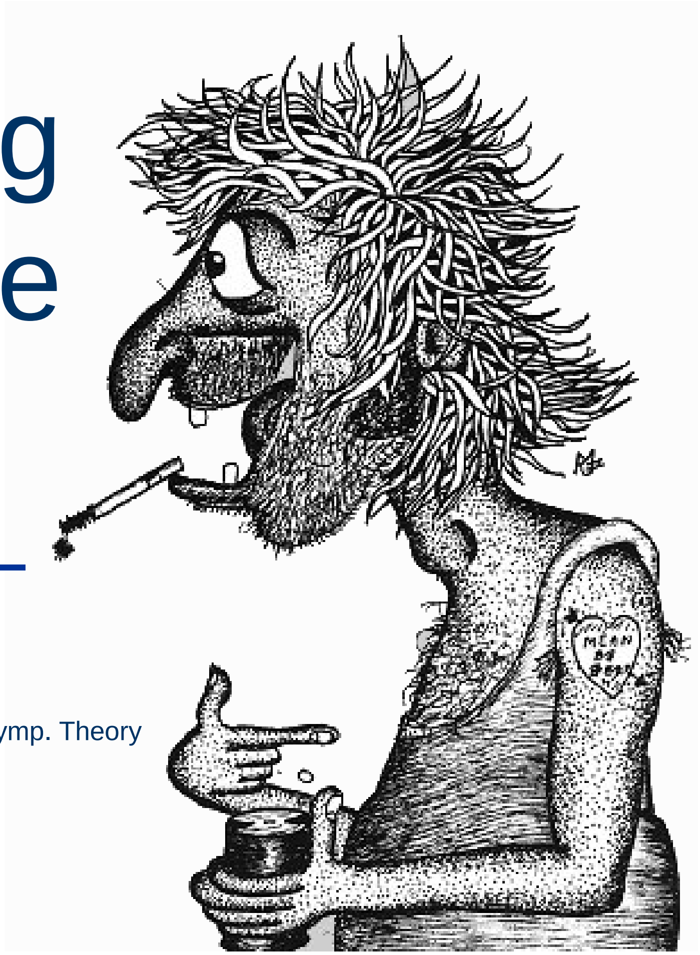
Faster Computer searches for a target of $B + 1$ =10001 bits in a year.



Does Quantum Computing Help?

Quantum computing reduces search time by a square root.

$\sqrt{}$



L. K. Grover, “A fast quantum mechanical algorithm for data search”, Proc. ACM Symp. Theory Computing, 1996, pp. 212--219.

Information Definitions

unassisted search: endogenous information

$$I_\Omega = -\log_2(p)$$

assisted search: endogenous information

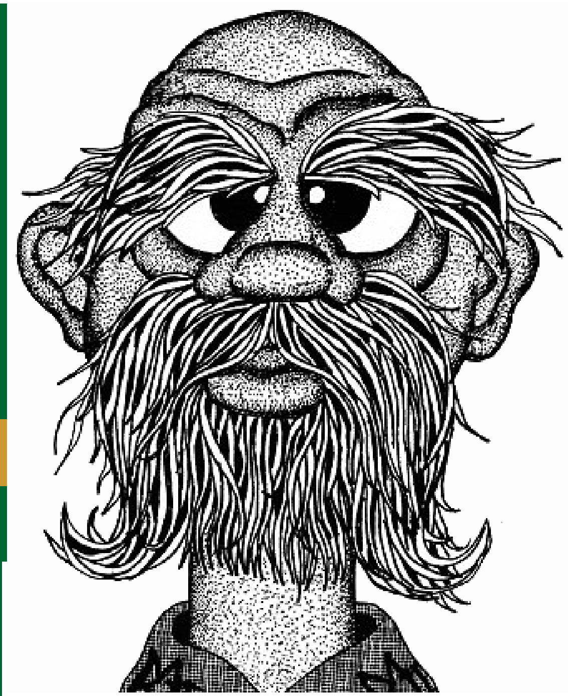
$$I_S = -\log_2(q)$$

difference: active information

unassisted search

$$I_+ = -\log_2\left(\frac{p}{q}\right)$$

assisted search



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Conservation of Information in Search: Measuring the Cost of Success

William A. Dembski, *Senior Member, IEEE,* and Robert J. Marks II, *Fellow, IEEE*

***Abstract*—Conservation of information theorems indicate that any search algorithm performs on average as well as random search without replacement *unless* it takes advantage of problem-specific information about the search target or the search-space structure. Combinatorics shows that even a moderately sized search requires problem-specific information to be successful. Computers, despite their speed in performing queries, are completely inadequate for resolving even moderately sized search problems without accurate information to guide them. We propose three measures to characterize the information required for successful search: (1) *endogenous information*, which measures the difficulty of finding a target using random search; (2) *exogenous information*, which measures the difficulty that**

[problems] you are working on, then no search strategy, no matter how sophisticated, can be expected to perform better than any other" [23]. Search can be improved only by "incorporating problem-specific knowledge into the behavior of the [optimization or search] algorithm" [46].

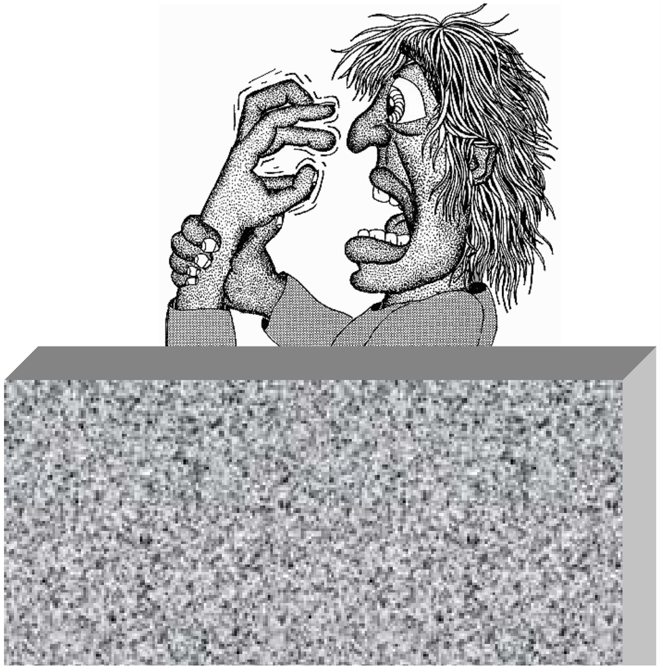
- English's *Law of Conservation of Information* [15] notes "the futility of attempting to design a generally superior optimizer" without problem-specific information about the search.

When applying Brillouin's insight to search algorithms (in-

SIMULATING EVOLUTION

Gregg Easterbrook

"Torture numbers, and they'll confess to anything."



Active Information in Partitioned Search...

METHINKS*IT*IS*LIKE*A*WEASEL

- XEHDASDSDDTTWSW*QITE*RIPOCFL
- XERXPLEE*ETSXSR*IZAW**LPAEWL
- MEQWASKL*RTPLSWKIRDOU*VPASRL

yada yada yada

Dawkins required 43 iterations

- METHINKS*IT*IS*LIKE*A*WEASEL

2. Active Information in Partitioned Search...

- METHINKS*IT*IS*LIKE*A*WEASEL

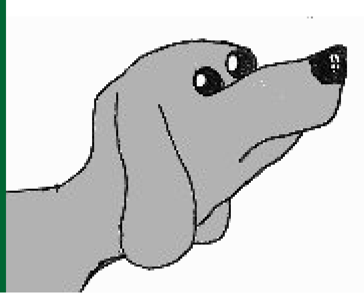
For unassisted search

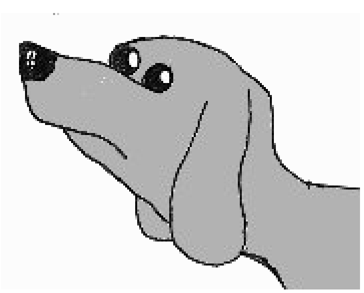
$$I_+ = \log_2(Q)$$

For Partitioned Search

$$I_+ \approx L \log_2(Q)$$

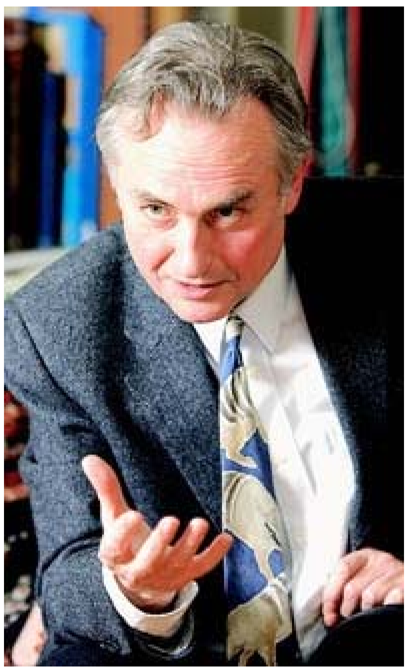
Hints amplify the added information by a factor of L.





Active
Information in Partitioned Search...

- Comparison



Reality: For Partitioned Search

$$Q \approx 43 \text{ iterations}$$

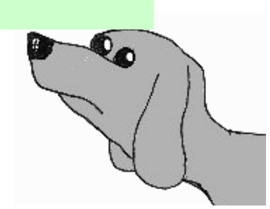
For Unassisted Search

$$Q \approx 1.1973 \times 10^{40} \text{ iterations}$$

There is a lot of active information.

METHINKS*IT*IS*LIKE*A*WEASEL

L= 28 characters, 27 in alphabet



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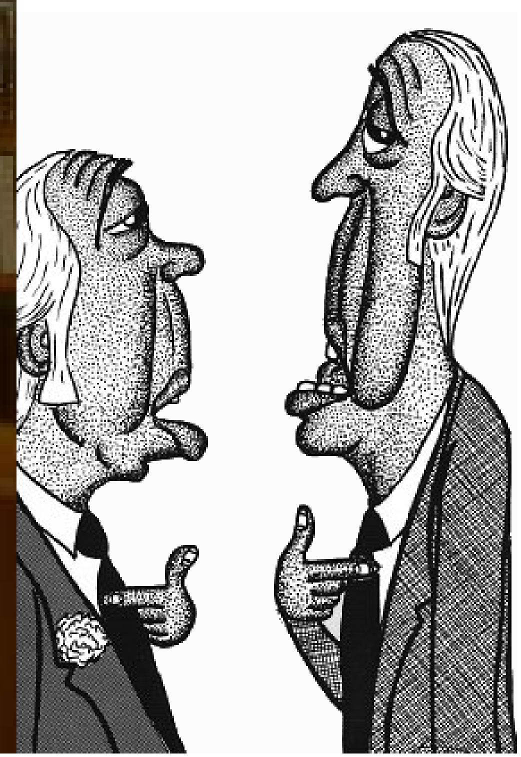
Domain knowledge can be applied differently resulting in varying degrees of active information

The knowledge used in partitioned search can be used to find all the letters and spaces in an arbitrarily large library using only 26 queries.



Weasel Wear on EvoInfo.org

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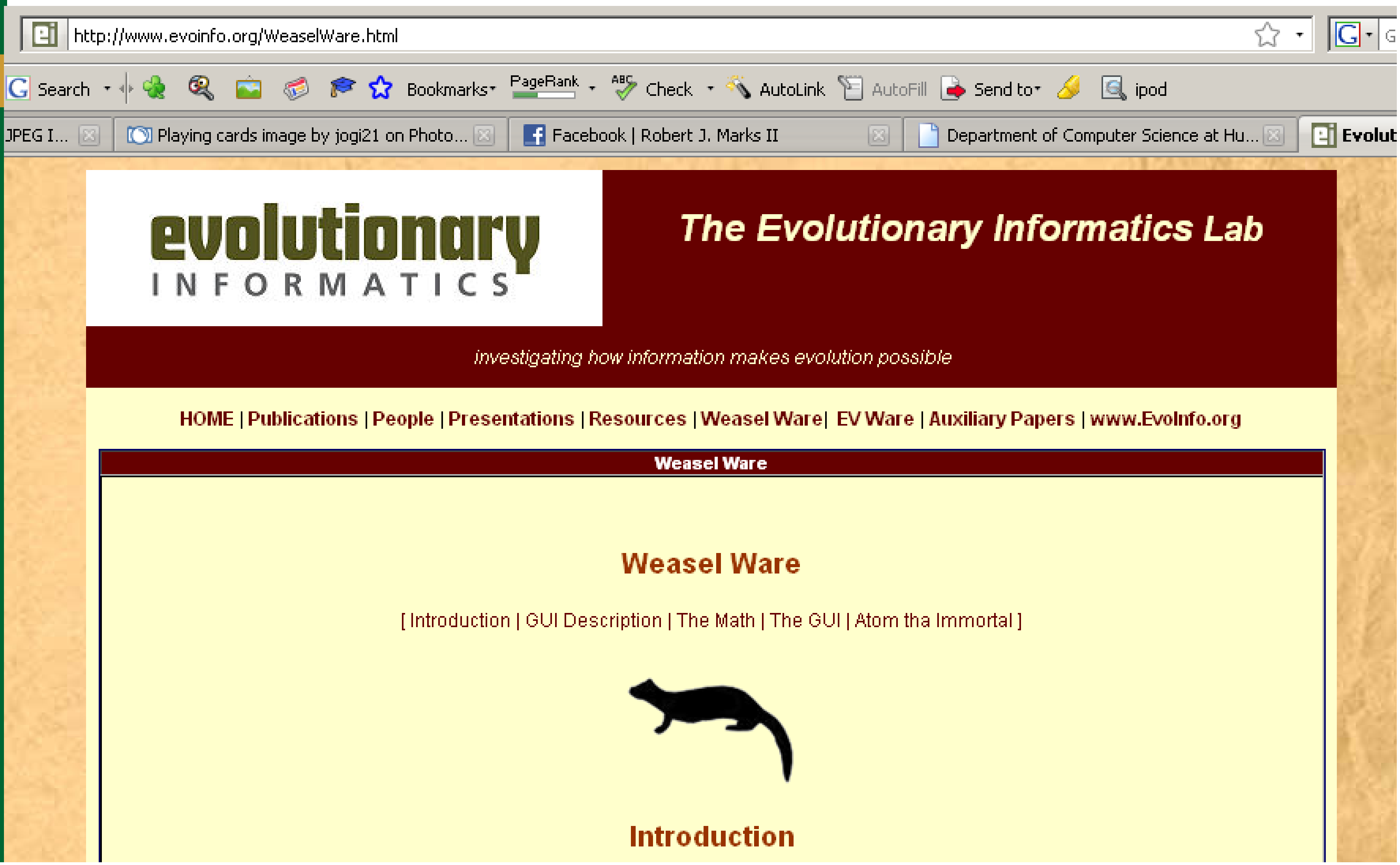

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EVOLUTION SIMULATIONS

2794–2799 Nucleic Acids Research, 2000, Vol. 28, No. 14

Evolution of biological information

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Received March 7, 2000; Revised and Accepted May 25, 2000

ABSTRACT

How do genetic systems gain information by evolutionary processes? Answering this question precisely requires a robust, quantitative measure of information. Fortunately, 50 years ago Claude Shannon defined information as a decrease in the uncertainty of a receiver. For molecular systems, uncertainty is closely related to entropy and hence has clear connections to the Second Law of Thermodynamics. These aspects of information theory have allowed the development of a straightforward and practical

These measurements show that there is a subtle connection between the pattern at binding sites and the size of the genome and number of sites. Relative to the potential for changes at binding sites, the size of the entire genome is approximately fixed over long periods of time. Even if the genome were to double in length (while keeping the number of sites constant), $R_{frequency}$ would only change by 1 bit, so the measure is quite insensitive. Likewise, the number of sites is approximately fixed by the physiological functions that have to be controlled by the recognizer. So $R_{frequency}$ is essentially fixed during long periods of evolution. On the other hand, $R_{sequence}$ can change rapidly and could have any value, as it depends on the details

Schneider's EV

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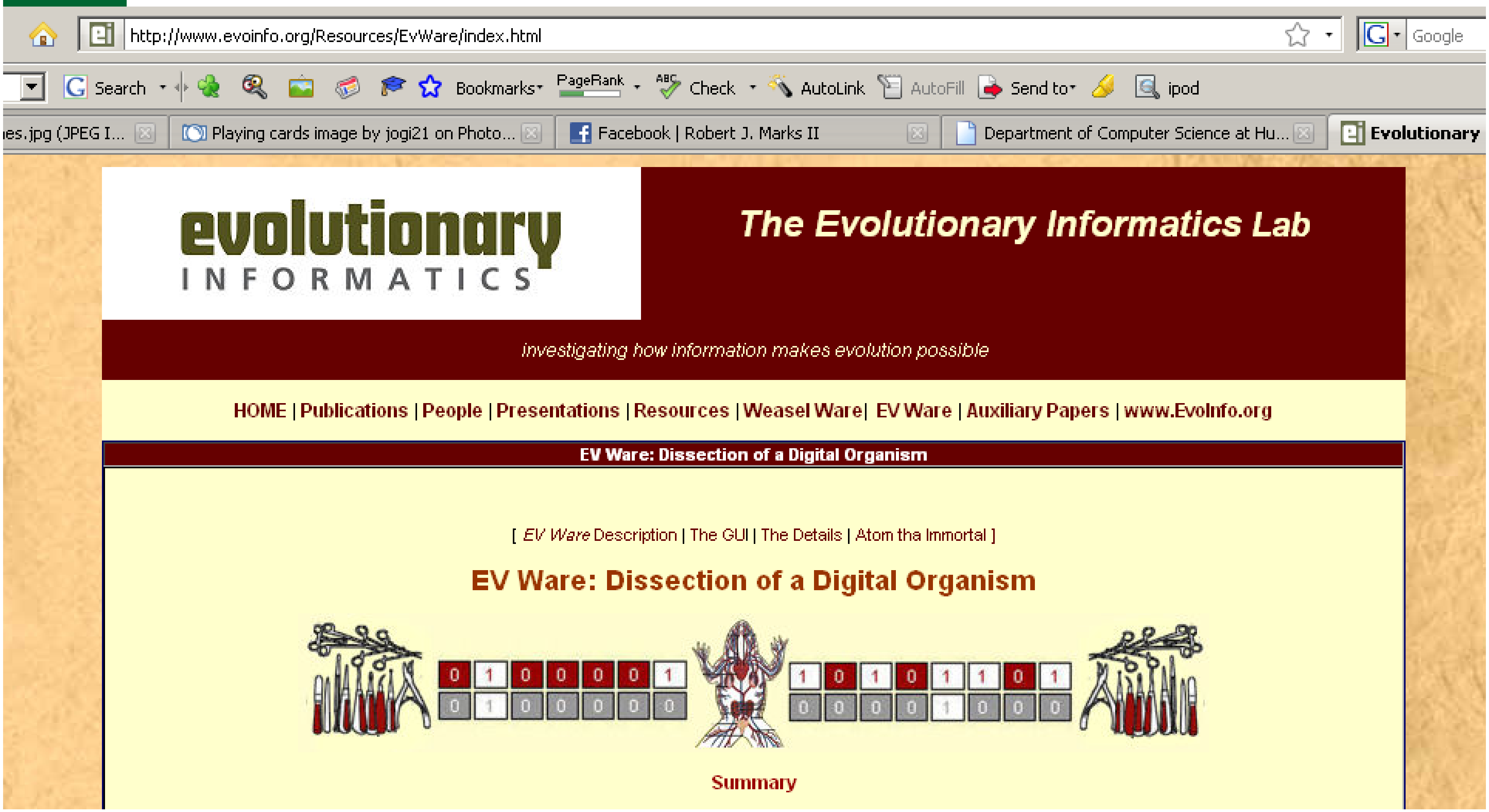
```
                     *         *10         *         *20         *         *30         *         *40
5' t c t t t g c a c g c t a a g t t t g t c a g g a a t t g t a a a c a c c t a a 3'
   --------- A -129    --------- G 450     --------- A 296     --------- G 4
             --------- C -442    --------- T -5      --------- C 251     --------- T 368

                     *         *50         *         *60         *         *70         *         *80
5' t c c g t c c a t g a t t t g t c t g a c c t a c a t t g t t g g a c g a g a a 3'
   --------- A -165    --------- G 254     --------- A 369     --------- G -95
             --------- C 334     --------- T -136    --------- C 251     --------- T -480

                     *         *90         *         *100        *         *110        *         *120
5' g c t c a t c g g g t a t g c c a g c g g g g c t g g a c g g t c a a t g g c a 3'
   --------- A -396    --------- G -199    --------- A -345    --------- G -304
             --------- C -150    --------- T 294     --------- C -378    --------- T -92

                     *         *130        *         *140        *         *150        *         *160
5' t t a c g c g c t g g c a t c t t a a a g a a t g a a c t a g a c t g a a c c g 3'
   --------- Threshold -58                                                     (------ ... EvSite-
                       (+++++++++++) EvSite+ 1 evaluation: 171
                                         (-----------) EvSite- 9 evaluation: -443
                                                       (-----------) EvSite- 16 evaluation: -1108

                     *         *170        *         *180        *         *190        *         *200
5' a c a a c t a g a c g c t t a a t t c a g c a a a a g c g g t g t a a a t a c a 3'
... -----) EvSite- 3 evaluation: -63                                            ( ... EvSite+
       (-----------) EvSite- 2 evaluation: -189              (-----------) EvSite- 13 evaluation: -509
                           (-----------) EvSite- 4 evaluation: -438
                                         (+++++++++++) EvSite+ 14 evaluation: 164

                     *         *210        *         *220        *         *230        *         *240
5' g g g g c g a g g a t c g c t a c c c g c a t t c t t c g a t c t c g t g g a g 3'
... +++++++++++) EvSite+ 7 evaluation: 159     (+++++++++++) EvSite+ 5 evaluation: 133
                           (-----------) EvSite- 6 evaluation: -516          (++ ... EvSite+
                 (-----------) EvSite- 10 evaluation: -645     (+++++++++++) EvSite+ 15 evaluation: 15

                     *         *250        *         *260        *
5' a t c c t t g a t g g t t a t a c t a c a t g c g a 3'
                 (+++++++++++) EvSite+ 8 evaluation: 600
... +++++++++) EvSite+ 11 evaluation: 619
                               (-----------) EvSite- 12 evaluation: -140
```

Schneider's EV

- Illusion: We find 131 nucleotide sights! Evolution finds something without $Q = 2^{131}$ queries! (704 needed)
- Truth: ev's Rube-Goldburg structure is packed with active information.
- Given resources: We can find all 131 binding sites in far less than 131 queries.

EV Ware on EvoInfo.org

George Montañez



ev & Avida

- The NFL theorem has been useful to address the "sometimes outrageous claims that had been made of specific optimization algorithms“

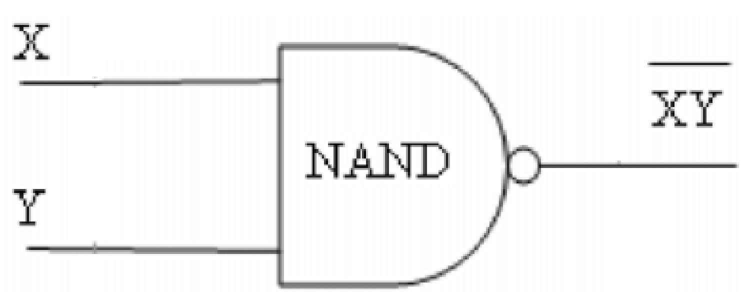
S. Christensen and F. Oppacher, "What can we learn from No Free Lunch? A First Attempt to Characterize the Concept of a Searchable,“ Proceedings of the Genetic and Evolutionary Computation (2001).

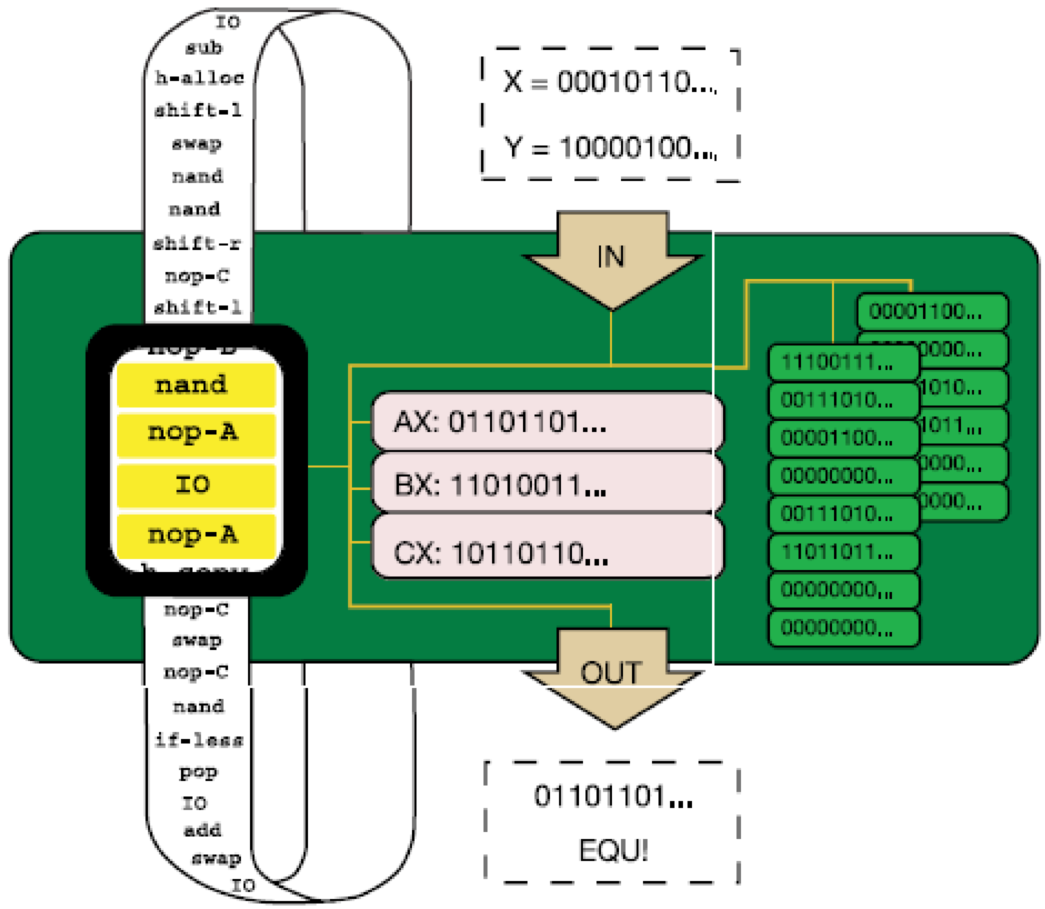
AVIDA

"… show how complex [biological] functions can originate by random mutation and natural selection."

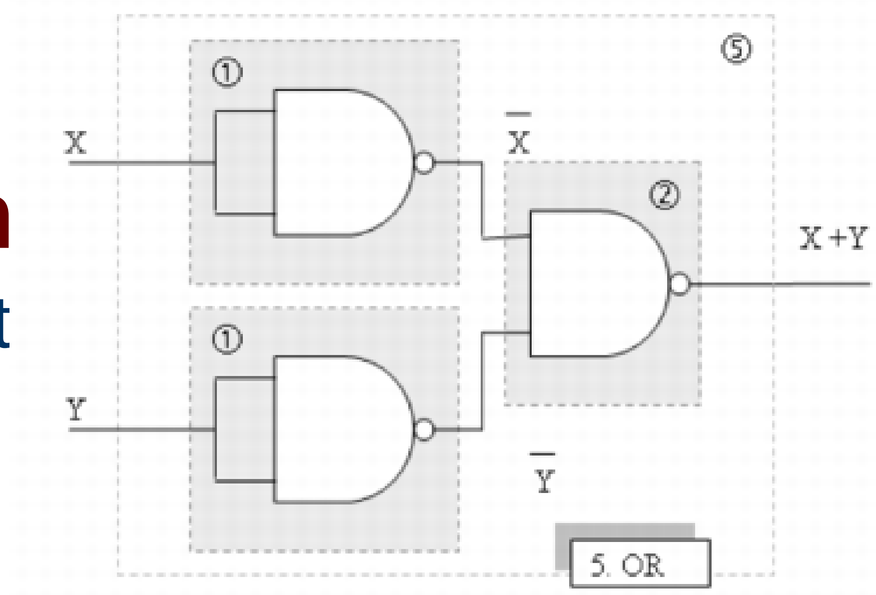
Logic	OUT	NANDS	Score
NOT	either $\overline{X}$ or $\overline{Y}$	1	2
NAND	$\overline{X\&Y}$	1	2
AND	X&Y	2	4
OR_N	either $X+\overline{Y}$ or $\overline{X}+Y$	2	4
OR	X+Y	3	8
AND_N	either $X\&\overline{Y}$ or $\overline{X}\&Y$	3	8
NOR	$\overline{X+Y}$	4	16
XOR	$X\oplus Y=(X\&\overline{Y})+(\overline{X}\&Y)$	4	16
EQU	$\overline{X\oplus Y}=(X\&Y)+(\overline{X}\&\overline{Y})$	5	32

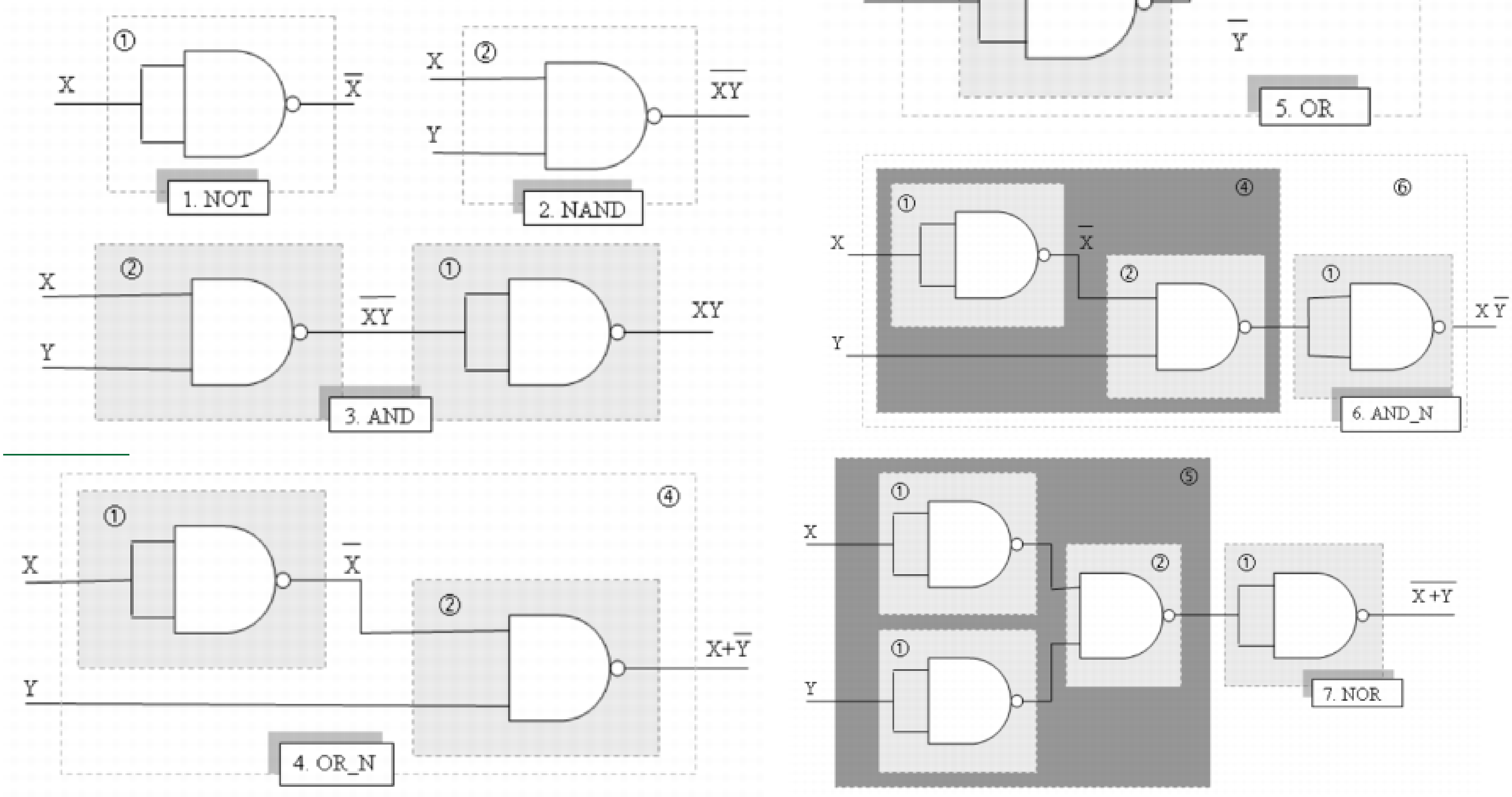
NAND logic





AVIDA:
Active Information
Stair Step Active Informat





AVIDA:
Active Information

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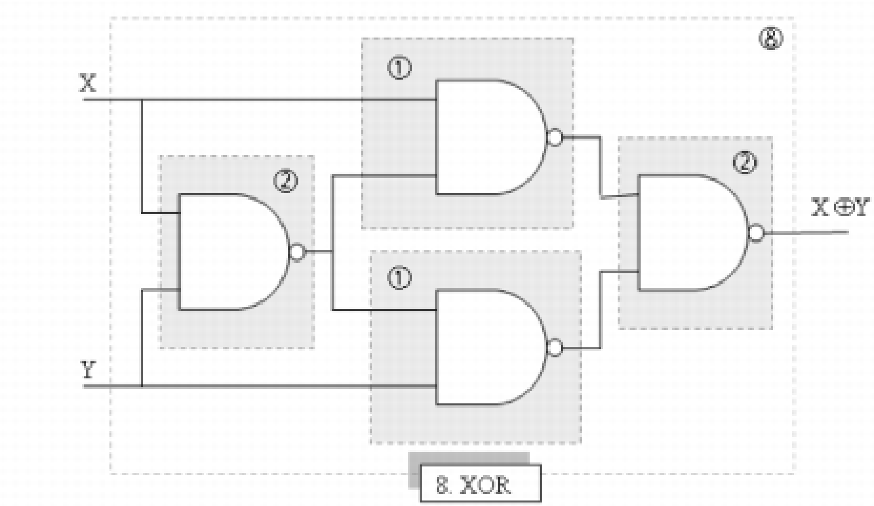
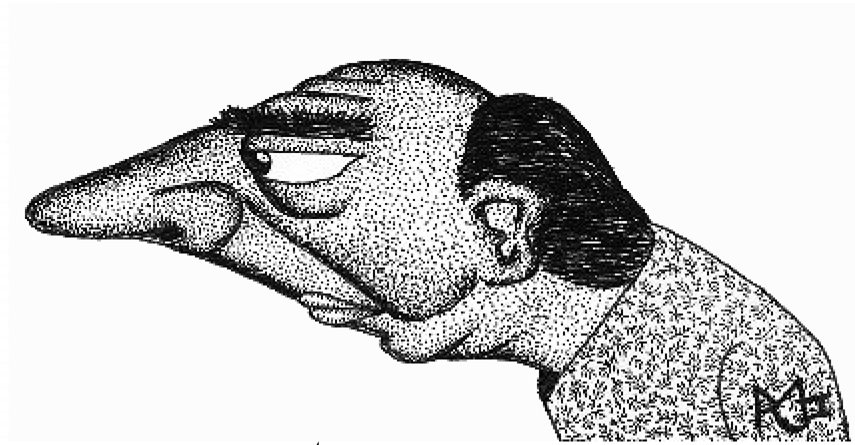
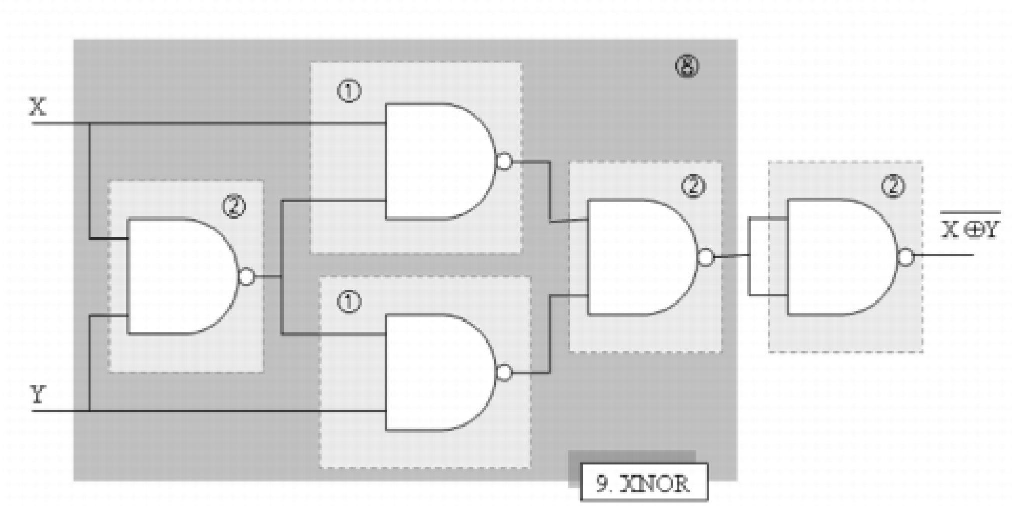
Stair Step Active Information





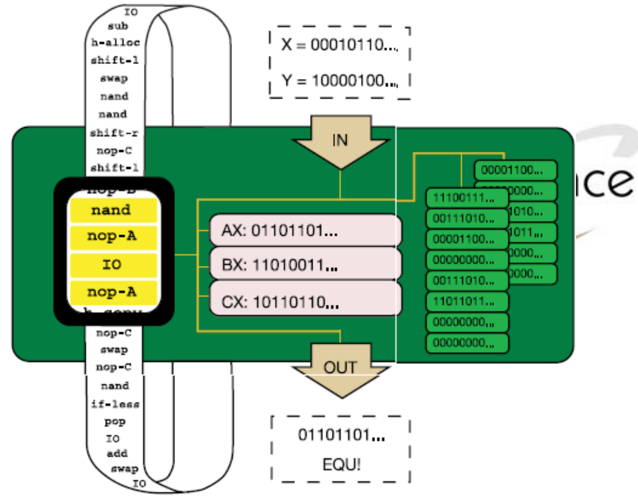


THE TARGET

(EQU = XNOR)

AVIDA:
Active Information

Stair Step Active Information



One Population:

3600 Organisms Evolved Using At Most About 10.8 Billion Instructions

Variations on a theme

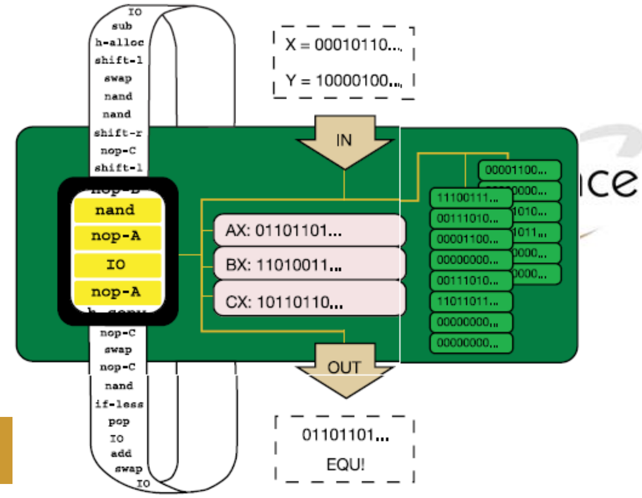
The case-study population was one of 50 that evolved under identical conditions, 23 of which acquired EQU.

Same Run, Using No Stepping Stones...

At the other extreme, 50 populations evolved in an environment where only EQU was rewarded, and no simpler function yielded energy. We expected that EQU would evolve much less often because selection would not preserve the simpler functions that provide foundations to build more complex features.

AVIDA:

Active Information



Endogenous Information of AVIDA

85 instructions per digital organism, 1420 runs of 10.8 billion instructions per run using importance sampling

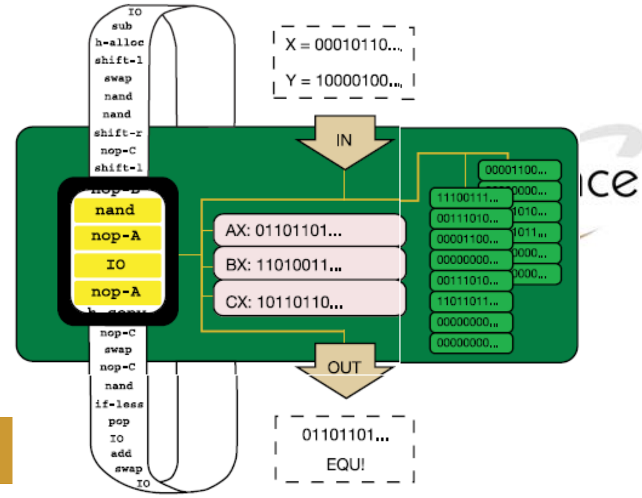
$$I_{\Omega} \cong 40 \text{ bits}$$

(20 nucleotides)

Winston Ewert, William A. Dembski and R.J. Marks II, “Evolutionary Synthesis of Nand Logic: Dissecting a Digital Organism," Proceedings of the 2009 IEEE International Conference on Systems, Man, and Cybernetics, October 11-14, 2009, San Antonio, Texas, USA.

AVIDA:

Active Information

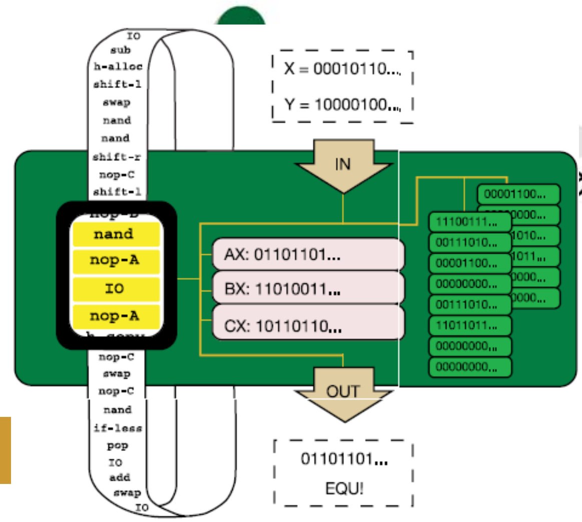


Active information introduced by AVIDA, including stair steps. 353 runs each. Normalized active information per instruction is in nanobits.

Model	Steps Removed	Successes	$I_{\oplus} / I_{\Omega}$
$\mathcal{A}_1$	None (All Steps Enabled)	346	1.90
$\mathcal{A}_2$	XOR/NOR	319	1.37
$\mathcal{A}_3$	XOR/NOR/OR/AND_N	227	0.62
$\mathcal{A}_4$	XOR/NOR/AND/OR_N	222	0.52

Winston Ewert, William A. Dembski and R.J. Marks II, “Evolutionary Synthesis of Nand Logic: Dissecting a Digital Organism," Proceedings of the 2009 IEEE International Conference on Systems, Man, and Cybernetics, October 11-14, 2009, San Antonio, Texas, USA.

Confession...



Stair step active information. In the initial description of Avida, the authors write [16]

> "Some readers might suggest that we stacked the deck by studying the evolution of a complex feature that could be built on simpler functions that were also useful."

AVIDA:

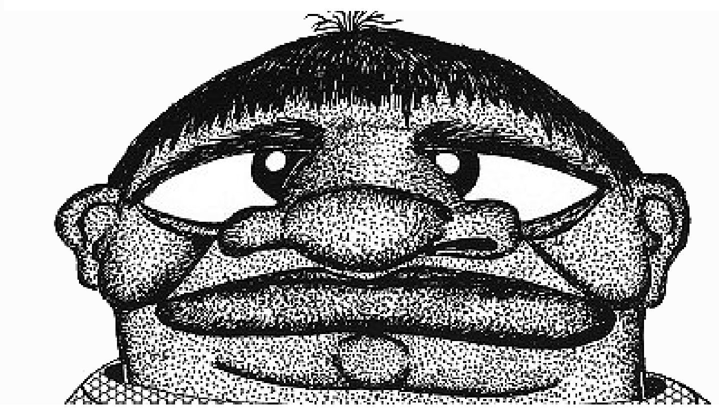
Evolutionary Simulation Integrity

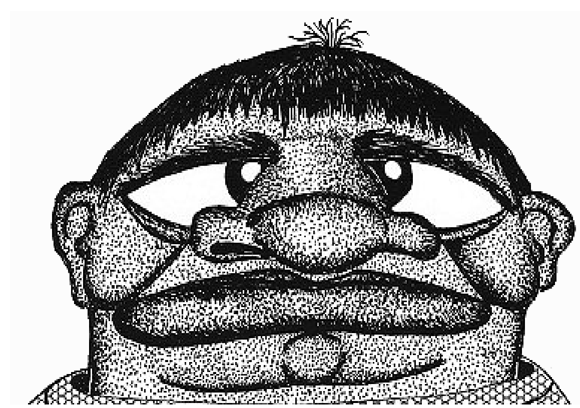
To have integrity, computer simulations of evolutionary search like Avida should make explicit

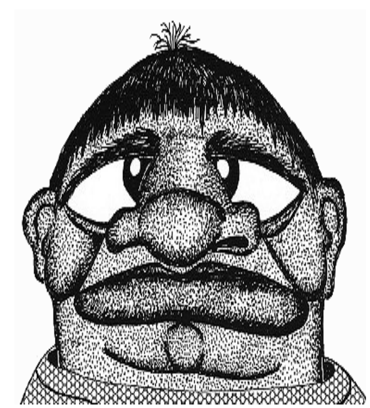
(1) a measure or assessment of the difficulty, I_Ω, of the problem being solved,

(2) the prior knowledge that gives rise to the active information in the search algorithm, and

(3) a measure or assessment of the active information, *e.g.* either I_+ or $I_\oplus$, introduced by the prior knowledge.







What is the source of active information?

- There must be active information in some way guide this process.
- Where does it come from?
- What about searching for a good search?

The Search for a Search: Measuring the Information Cost of Higher Level Search

William A. Dembski and Robert J. Marks II

***Abstract*—Many searches are needle-in-the-haystack problems, looking for small targets in large spaces. In such cases, blind search stands no hope of success. Success, instead, requires an assisted search. But whence the assistance required for a search to be successful? To pose the question this way suggests that successful searches do not emerge spontaneously but need themselves to be discovered via a search. The question then naturally arises whether such a higher-level "search for a search" is any easier than the original search. We prove two**

arbitrary search space structure will, on average, result in a worse search than assuming nothing and simply performing an unassisted search.

The Horizonal NFLT addresses how changing a search space structure affects average search performance, but it does not address the difficulty of finding a search capable of locating a particular target. That is the job of the Vertical NFLT, which characterizes the information costs of searching higher-level search spaces for suc-

What is the source of active information?

- Search for the Search ?

  The endogenous information for the search increases exponentially with respect to the active information

$$\widehat{I}_{\Omega} \simeq 2^{I_+} \text{ bits}$$

REGRESS: Search for the Search for the Search

Creator Of Information

Mass, Energy, Space, Time ... Information

1. "In the beginning God created the heavens and the earth."
2. "Now the earth was formless and empty, darkness was over the surface of the deep, and the Spirit of God was hovering over the waters."

No Information

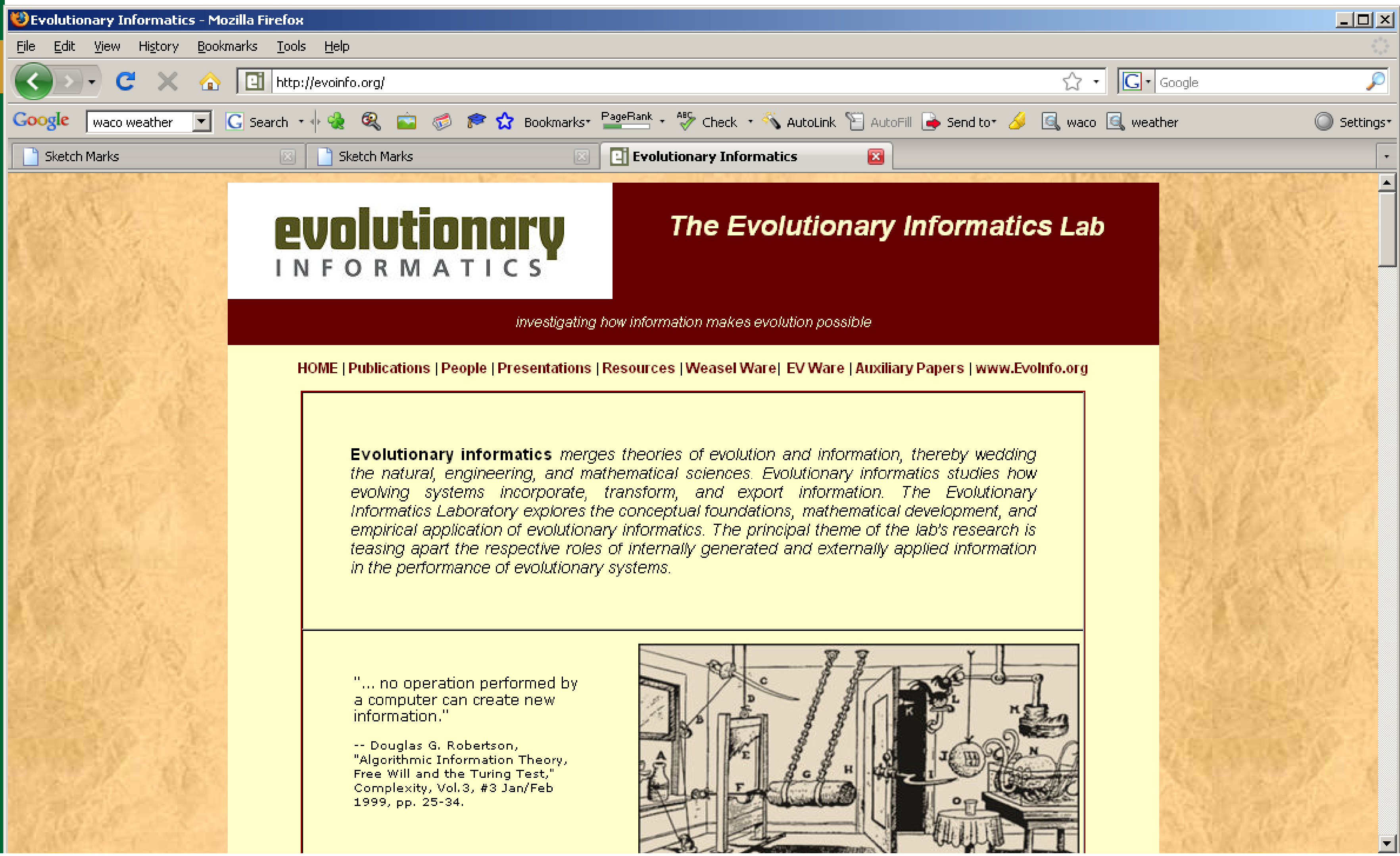
Information Creation

And God said, "Let there be light," ... "Let the water under the sky be gathered to one place, and let dry ground appear." "Let the land produce vegetation." "Let the water teem with living creatures, and let birds fly..." "Let the land produce living creatures according to their kinds..." "Let us make man in our image, in our likeness, and let them rule over the fish of the sea and the birds of the air, over the livestock, over all the earth, and over all the creatures that move along the ground."

Information & Structure

Baylor University Engineering & Computer Science

EvoInfo.org




THAT'S A PRETTY STUPID QUESTION JOHN. I'M AFRAID I'LL HAVE TO KILL YOU.

Baylor University
Engineering & Computer Science