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School of Economics

Explaining the evolution of technologies, firms, and industries: *How complexity and constraints can be simulated*

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Background

PhD research topic: The effects of resource scarcity on innovation (prof. Liisa Välikangas)

Research question(s): why scarcities sometimes result to significant innovations, but not always?

Framework: evolutionary theory and complex, non-linear behavior (complexity); information theory; theory of computation; simulation models

Unit of analysis: technology/system as artefact

Why I'm here: to outline some ideas!

Agenda

How the world works - information and evolution

Systems as strings of information

Problem-solving as search process

Why interdependency matters

Fitness landscapes

Development of flash smelting

Effects of scarcity, and measuring innovation

Some implications



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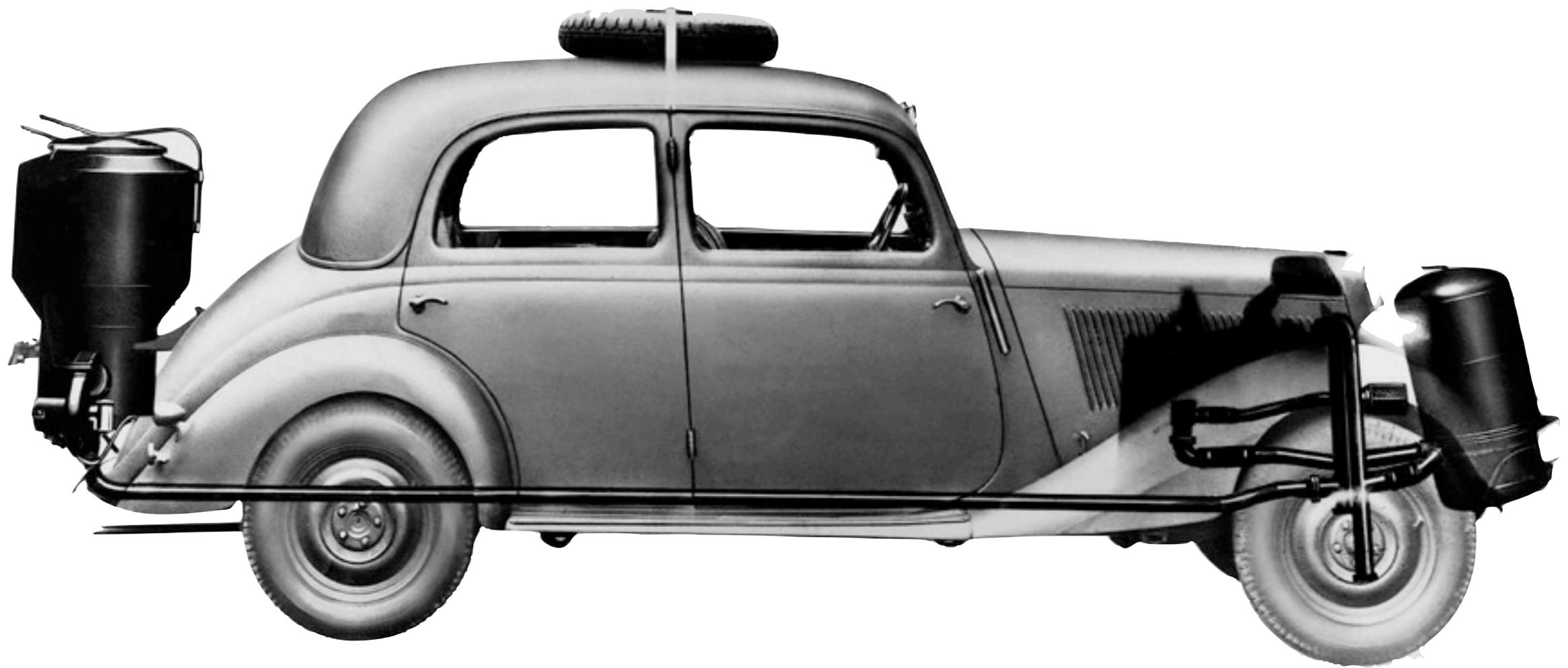
Some implications



Why...

...some technologies get adopted, and others are discarded?

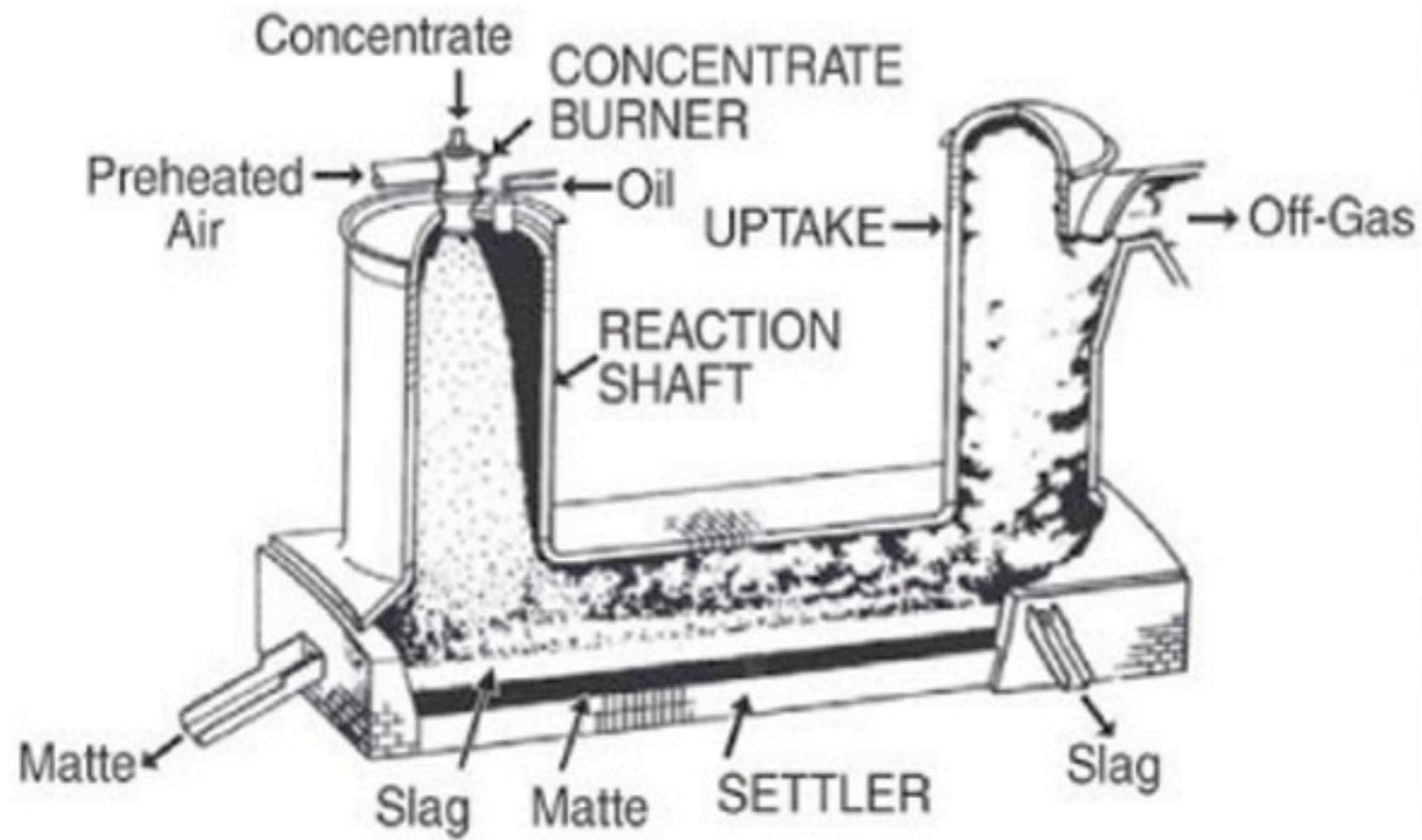




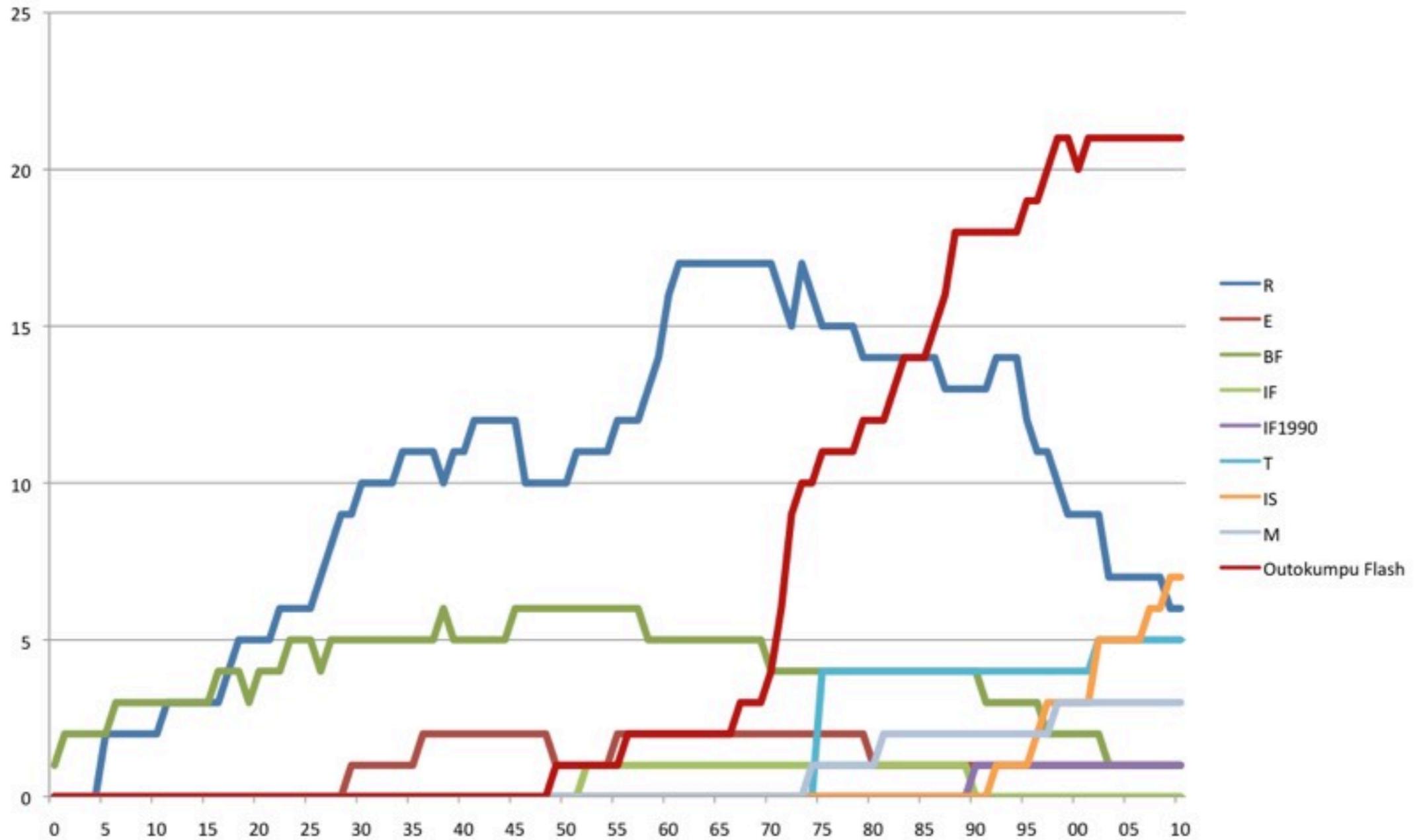
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King (2007)



To find out why,
let's take a look how the world works



The world *is* information





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(c) Warner / Village Roadshow

...describing a *system*

```
1 GATCCTCCAT ATACAACGGT ATCTCCACCT CAGGTTTAGA TCTCAACAAC
GGAACCATTG
61 CCGACATGAG ACAGTTAGGT ATCGTCGAGA GTTACAAGCT AAAACGAGCA GTAGTCAGCT
121 CTGCATCTGA AGCCGCTGAA GTTCTACTAA GGGTGGATAA CATCATCCGT GCAAGACCAA
181 GAACCGCCAA TAGACAACAT ATGTAACATA TTTAGGATAT ACCTCGAAA TAATAAACCG
241 CCACACTGTC ATTATTATAA TTAGAAACAG AACGCAAAA TTATCCACTA TATAATTCAA
301 AGACGCGAAA AAAAAAGAAC AACGCGTCAT AGAACTTTTG GCAATTCGCG TCACAAATAA
361 ATTTTGGCAA CTTATGTTTC CTCTTCGAGC AGTACTCGAG CCCTGTCTCA AGAATGTAAT
421 AATACCCATC GTAGGTATGG TTAAAGATAG CATCTCCACA ACCTCAAAGC TCCTTGCCGA
481 GAGTCGCCCT CCTTTGTCGA GTAATTTTCA CTTTTCATAT GAGAACTTAT TTTCTTATTC
541 TTTACTCTCA CATCCTGTAG TGATTGACAC TGCAACAGCC ACCATCACTA GAAGAACAGA
601 ACAATTA CTT AATAGAAAA TTATATCTTC CTCGAAACGA TTTCCCTGCTT CCAACATCTA
661 CGTATATCAA GAAGCATTCA CTTACCATGA CACAGCTTCA GATTTTCATTA TTGCTGACAG
721 CTACTATATC ACTACTCCAT CTAGTAGTGG CCACGCCCTA TGAGGCATAT CCTATCGGAA
781 AACAAATACC CCCAGTGGCA AGAGTCAATG AATCGTTTAC ATTTCAAATT TCCAATGATA
841 CCTATAAATC GTCTGTAGAC AAGACAGCTC AAATAACATA CAATTGCTTC GACTTACCGA
901 GCTGGCTTTC GTTTGACTCT AGTTCTAGAA CGTTCTCAGG TGAACCTTCT TCTGACTTAC
961 TATCTGATGC GAACACCACG TTGTATTTCA ATGTAATACT CGAGGGTACG GACTCTGCCG
1021 ACAGCACGTC TTTGAACAAT ACATACCAAT TTGTTGTTAC AAACCGTCCA TCCATCTCGC
1081 TATCGTCAGA TTTCAATCTA TTGGCGTTGT TAAAAAATA TGGTTATACT AACGGCAAAA
1141 ACGCTCTGAA ACTAGATCCT AATGAAGTCT TCAACGTGAC TTTTGACCGT TCAATGTTCA
```

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Everything can be coded



(c) Hartwall/Kumpula, Jack Daniels

Describing a system...

	0	1
Material	Glass	Plastic
Shape	Round	Square
Contents	No pressure	Under pressure
Cap	Pull	Screw

Leftmost column represents elements, 0 and 1 columns represent alleles of an element

Describing a system...

	0	1
Material		
Shape		
Contents		
Cap		

Describing a system...

	0	1
Material		
Shape		
Contents		
Cap		

...system as *strings*

		
Material	0	1
Shape	1	0
Contents	0	1
Cap	0	1

Bottles are thus coded in terms of their elements and alleles (e.g. Frenken 2001, 2006)

What *can* be coded?

In principle, everything that is definable by information \approx *everything!* Applications include

- **Organization theory** (*Kauffman and Macready 1995; Westhoff et al 1996; Levinthal 1997; Marengo 1998; Baum 1999; Levinthal and Warglien 1999; McKelvey 1999a, 1999b; Gavetti and Levinthal 2000; Ghemawat and Levinthal 2000; Marengo et al. 2000; Rivkin 2000; Dosi et al. 2001; Frenken 2001, 2006; Morel and Ramanujam 1999*)
- **Political science** (*Schrodts 1994; Post and Johnson 2000*)
- **Scientometrics** (*Scharnhorst 1998*)

Strings for two bottles:

Jdaniels	0	1	0	0
ED	1	0	1	1

Bottles coded with four elements of two alleles;
e.g. Frenken (2001, 2006), Kauffman (1993)

All possible strings:

1	0	0	0	0	9	1	0	0	0
2	0	0	0	1	10	1	0	0	1
3	0	0	1	0	11	1	0	1	0
4	0	0	1	1	12	1	0	1	1
5	0	1	0	0	13	1	1	0	0
6	0	1	0	1	14	1	1	0	1
7	0	1	1	0	15	1	1	1	0
8	0	1	1	1	16	1	1	1	1

4-element, 2-allele design space (S) has $2^4 = 16$ possibilities

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Problem solving task:

Following Simon (1969), can be conceptualized as *searching* for the right solution in a solution (“design”) space.

New variations can be considered as “new combinations” (cf. Schumpeter 1934).

Due to practical limitations - the size of design space - this search is *boundedly rational*.

It thus requires *heuristics*.

1	0	0	0	0
2	0	0	0	1
3	0	0	1	0
4	0	0	1	1
5	0	1	0	0
6	0	1	0	1
7	0	1	1	0
8	0	1	1	1

9	1	0	0	0
10	1	0	0	1
11	1	0	1	0
12	1	0	1	1
13	1	1	0	0
14	1	1	0	1
15	1	1	1	0
16	1	1	1	1

Jdaniels is variation 5, ED is variation 12

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Interdependency *matters*

The system may have interdependent elements; “mutating” one may have an effect on another’s “fitness” for purpose.

This defines the system’s *architecture*.

Example:



(c) Hartwall/Kumpula

Example:

Pressurized contents



(c) Hartwall/Kumpula

Example:

Pressurized contents



Round shape

This is known as *epistasy*. Pressure has an *epistatic relationship* to the shape of bottle.

No epistasy

	Material	Shape	Contents	Cap
Material	x			
Shape		x		
Contents			x	
Cap				x

Kauffman (1993), Frenken (2001, 2006)

Epistatic relationship - 1

	Material	Shape	Contents	Cap
Material	x			
Shape		x	x	
Contents		x	x	
Cap				x

Changing the contents of the bottle may mean that the shape is no longer satisfactory

Epistatic relationship - 2

	Material	Shape	Contents	Cap
Material	x	x	x	
Shape	x	x	x	
Contents	x	x	x	x
Cap			x	x

Similarities to e.g. Quality Function
Deployment Matrix are evident.

This creates difficulties

As epistasy increases, finding the optimal solution becomes more and more difficult.

This can be represented using a *fitness landscape*:

- 1) assign a *fitness* to each solution
- 2) order the solutions based on their differences

Theoretically, three different landscapes can be identified:

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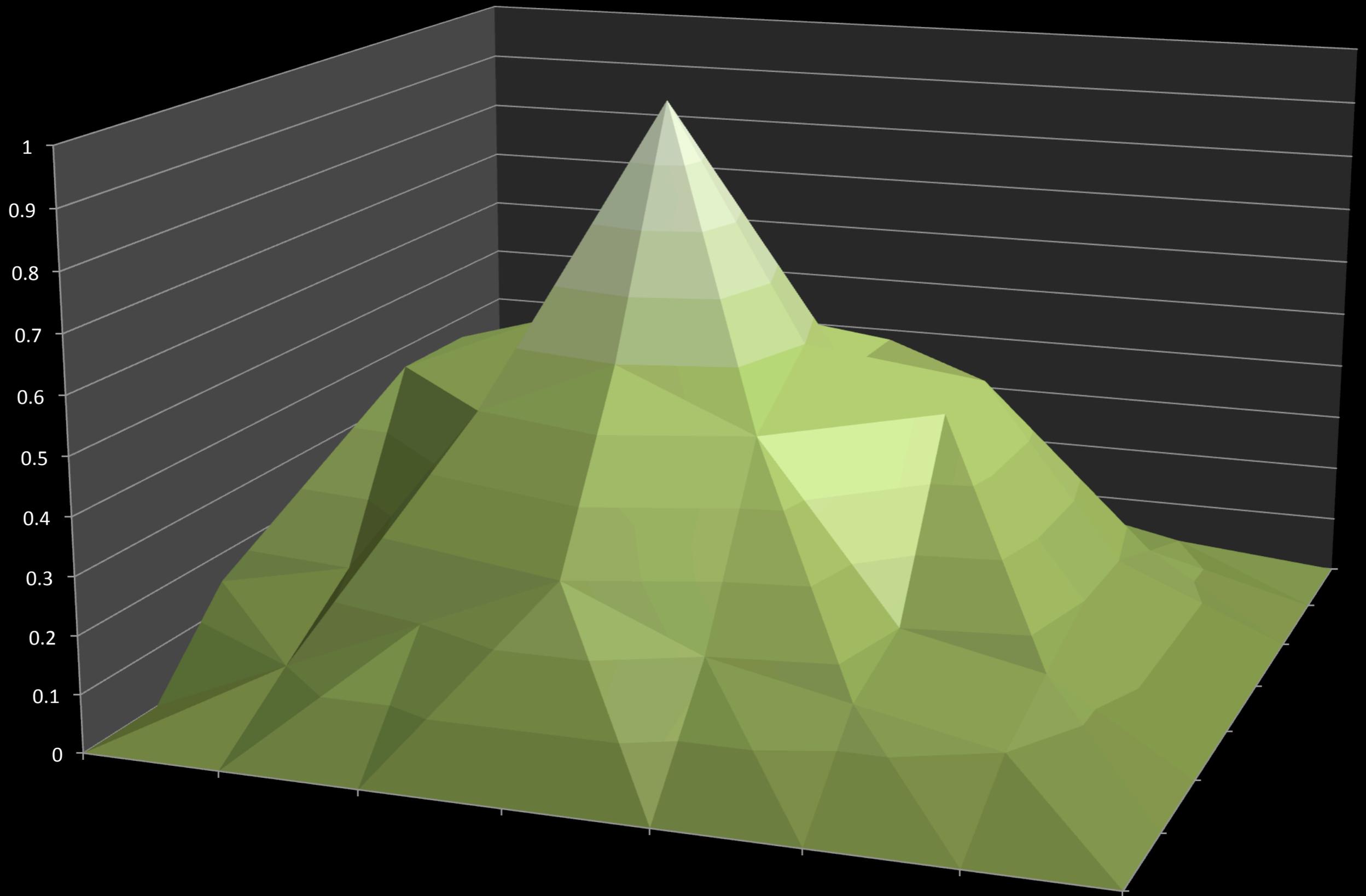
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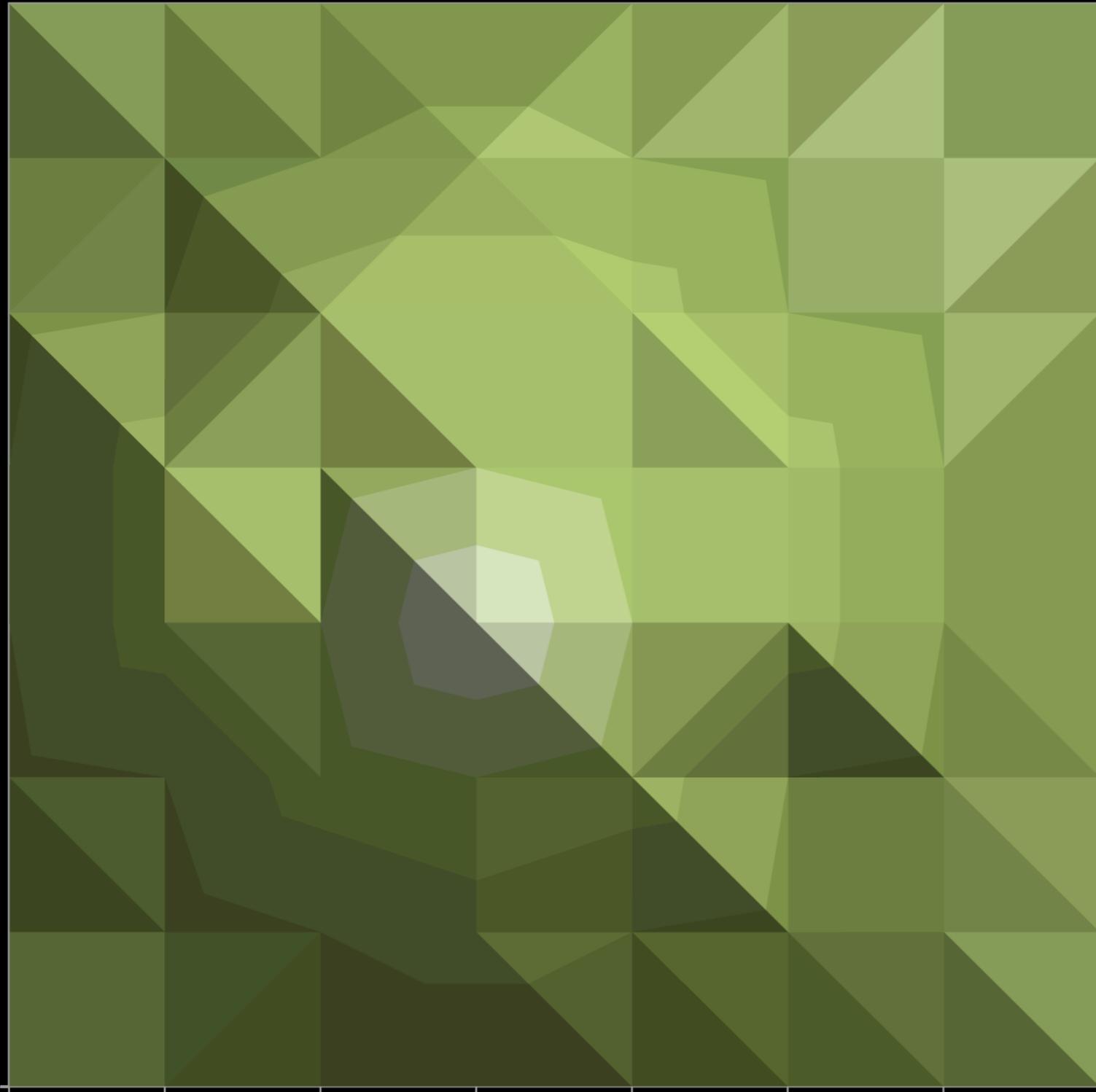
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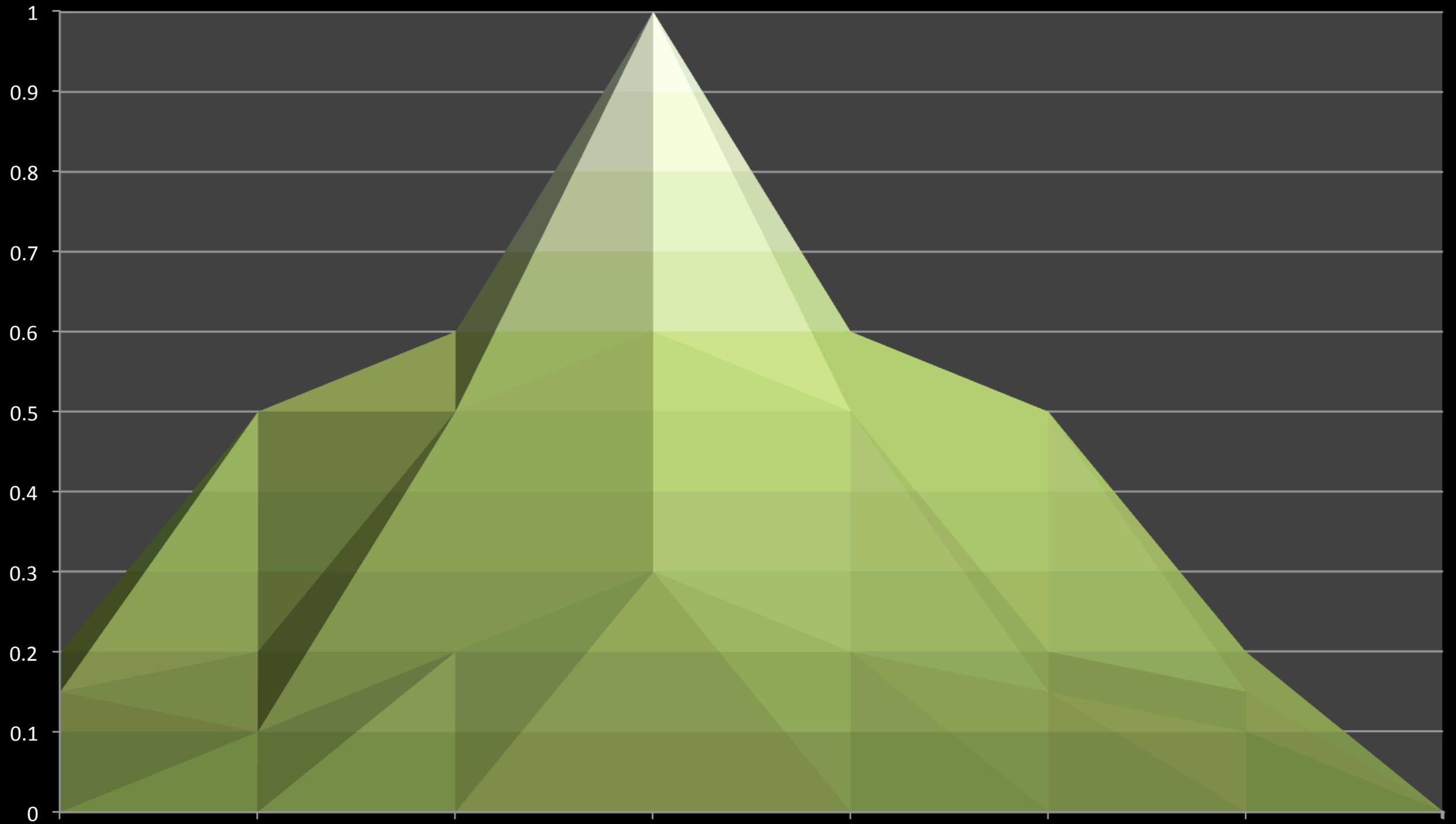


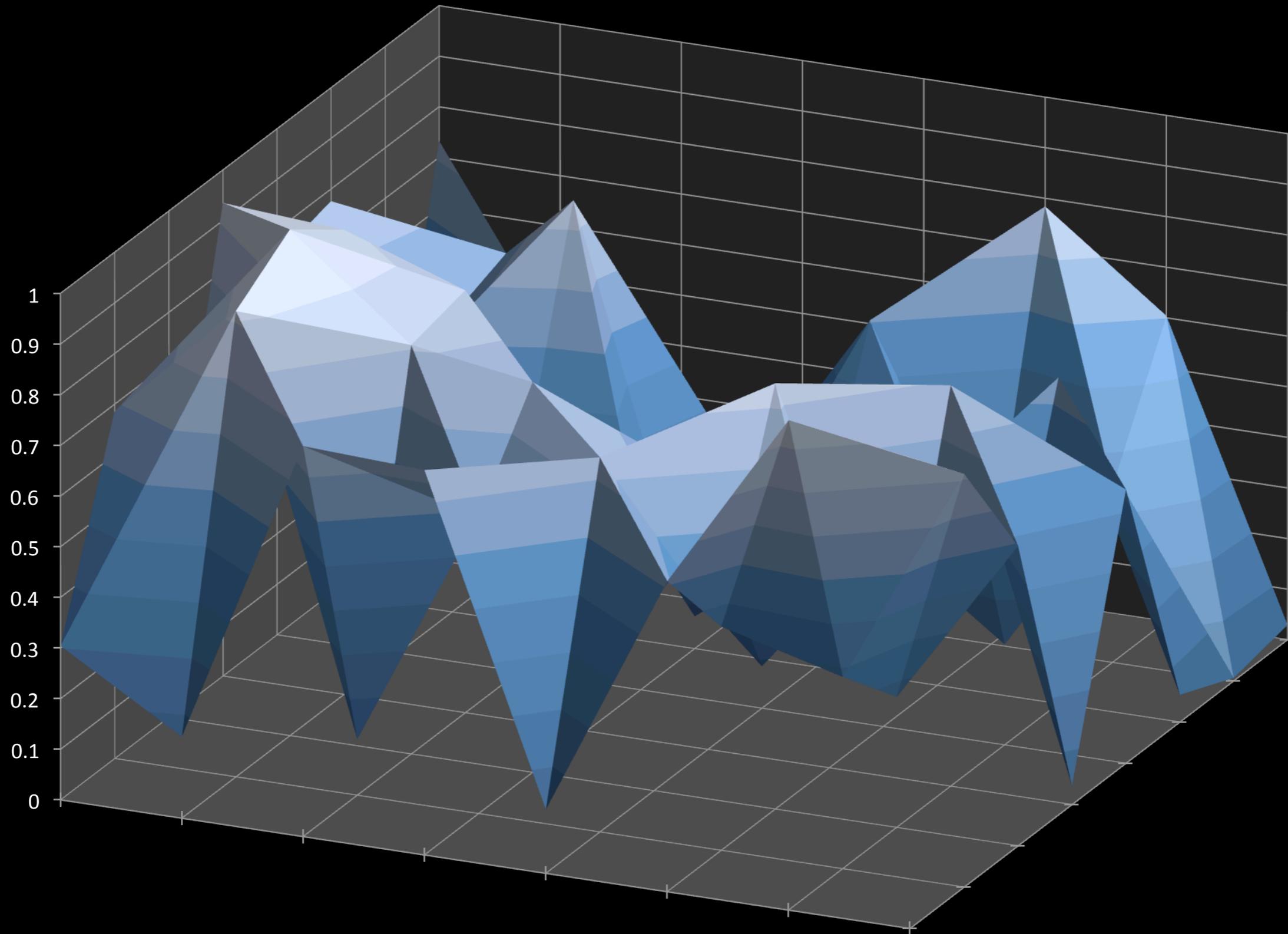
No epistasy: single solution is the best one for the task. Optimization is very easy.



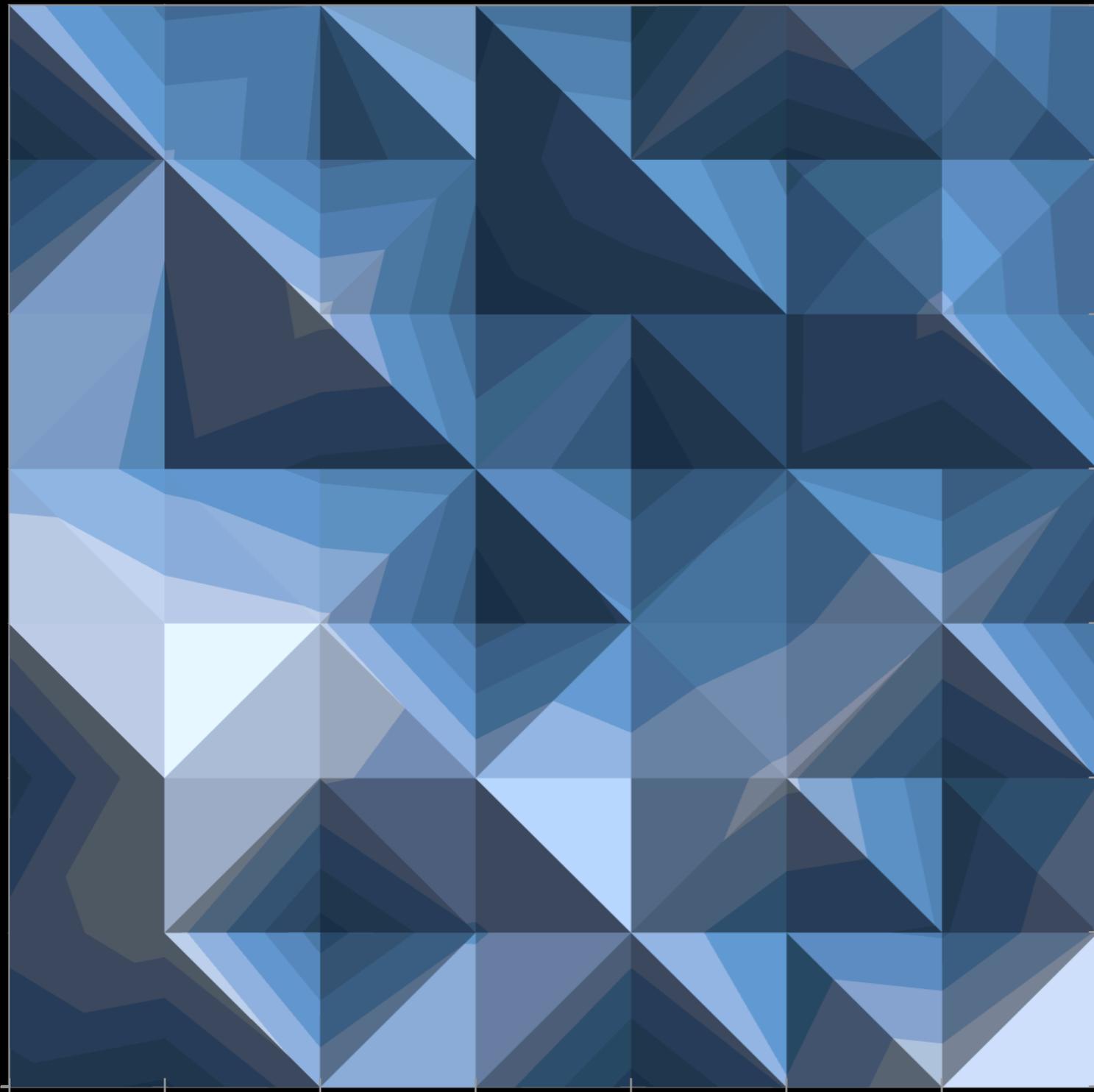
Fully correlated
landscape: one
fitness peak.

“Hill-climbing”
optimization
strategy works
every time.





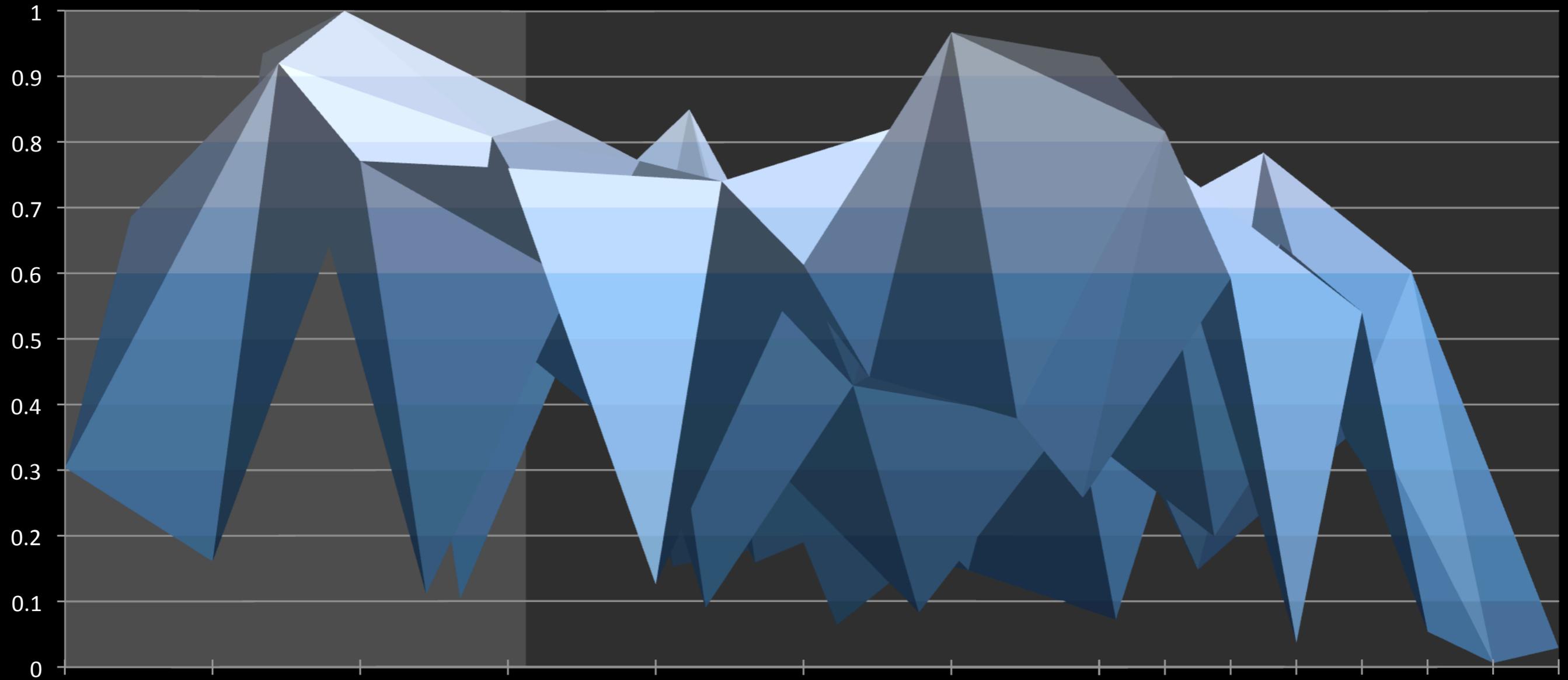
Chaotic landscape: maximum epistasy. No correlation between difference and fitness.

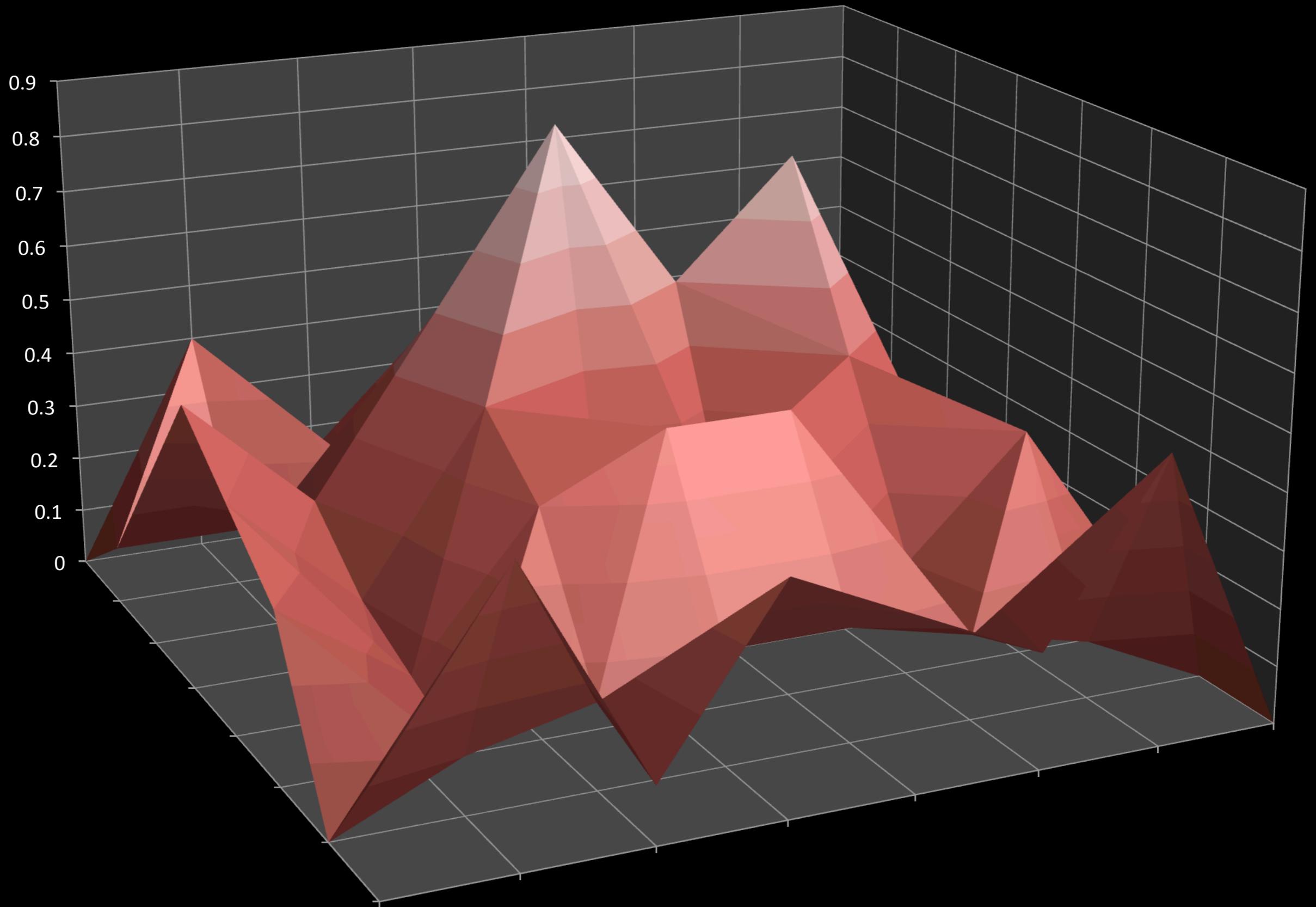


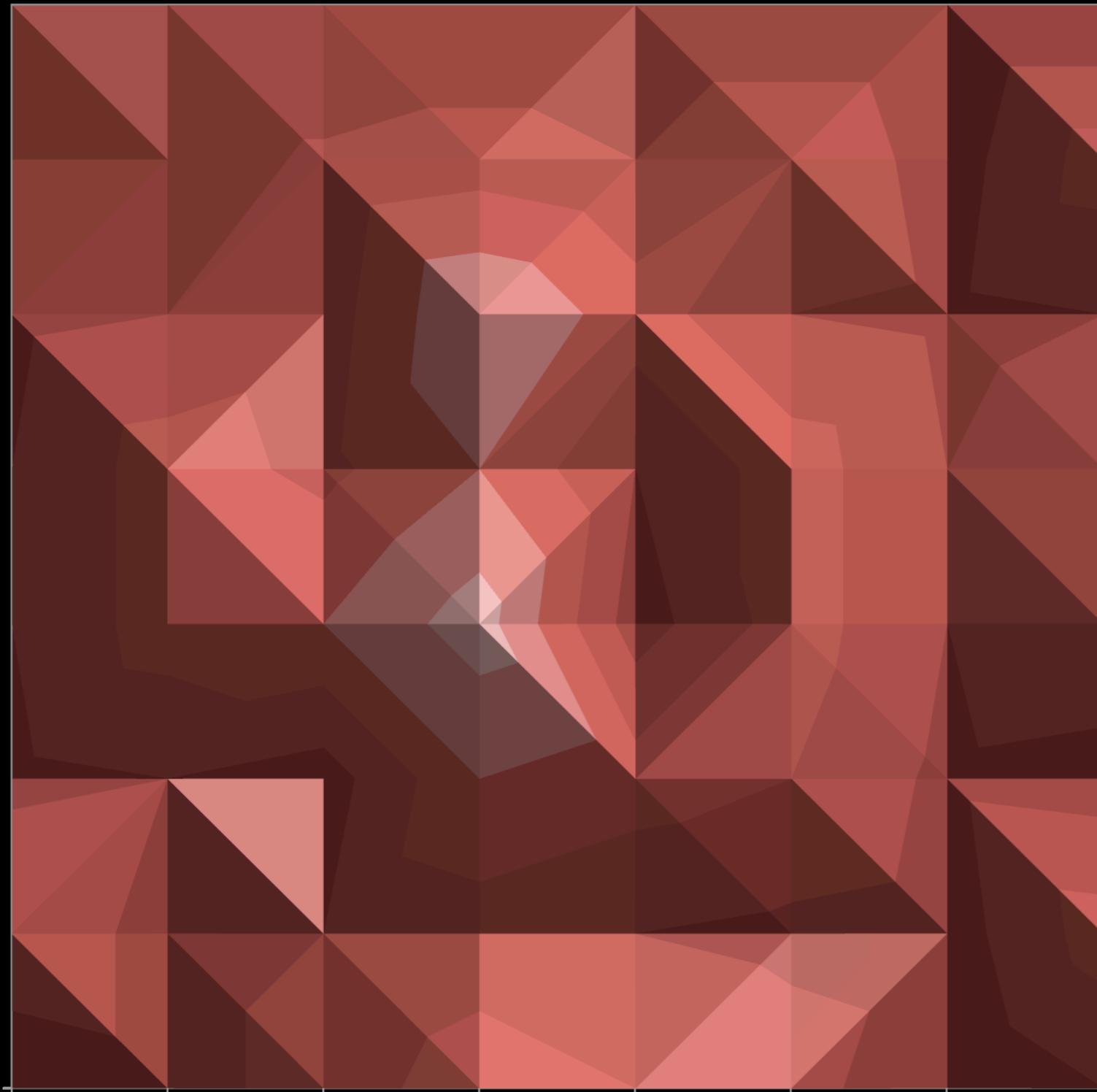
Chaotic landscape:
no correlation
between difference
and fitness.

Optimization
impossible; *random
search* only viable
search strategy.

e.g. Kauffman (1993, 2000); Frenken (2001,
2006)

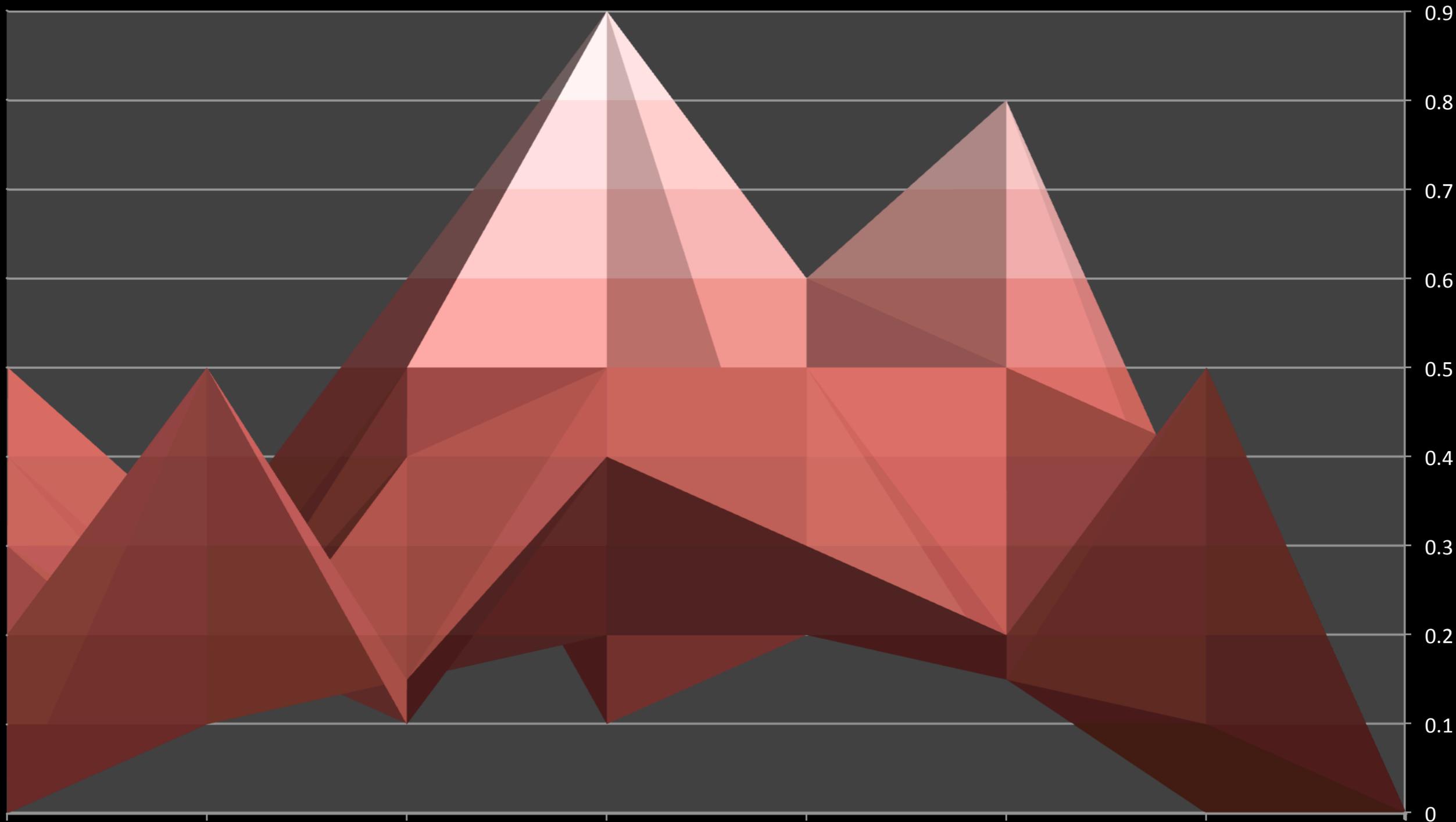






Roughly correlated landscape: fitness peaks and valleys.

Simple hill-climbing may get stuck to local optima; random search too inefficient. *Random mutation hill climbing works!*



Hello, real-life problem! This is what they tend to look like.

The neat thing:

We can *simulate* various problem-solving situations *without having to know the details of the situation*;

We just need to estimate the epistasy and solution space.

Arbitrarily large solution spaces

1	000000	17	010000	33	100000	49	110000
2	000001	18	010001	34	100001	50	110001
3	000010	19	010010	35	100010	51	110010
4	000011	20	010011	36	100011	52	110011
5	000100	21	010100	37	100100	53	110100
6	000101	22	010101	38	100101	54	110101
7	000110	23	010110	39	100110	55	110110
8	000111	24	010111	40	100111	56	110111
9	001000	25	011000	41	101000	57	111000
10	001001	26	011001	42	101001	58	111001
11	001010	27	011010	43	101010	59	111010
12	001011	28	011011	44	101011	60	111011
13	001100	29	011100	45	101100	61	111100
14	001101	30	011101	46	101101	62	111101
15	001110	31	011110	47	101110	63	111110
16	001111	32	011111	48	101111	64	111111

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Back to real life!

R	0000	0000	0000	0000	IF1950	0022	1120	2110	0101
R1930	0000	0001	0001	0110	IF1990	0022	1121	2111	3001
Rdry	0000	1100	0000	0100					
ROX	0001	0000	0000	0100	T	0121	0010	1010	0200
					Tdry	0131	1110	2110	2200
E1930	0010	0110	1101	0000	C	0021	1121	2101	1101
E1950	0010	0110	1100	0000	IS	1121	0020	2101	0300
					V	0022	0020	2110	0200
F1950	1120	1121	2121	0111	M	1121	1121	2110	0300
F1970	1121	1121	2121	0111	BF	1100	2000	0010	0200
F1990	1131	1121	2121	0101	PY	1120	2000	0010	0200

Development of flash smelting

BF 1100 2000 0010 0200 R 0000 0000 0000 0000

In 1900, blast (BF) and reverberatory (R) furnaces are widespread.

Development of flash smelting

BF	1100	2000	0010	0200	R	0000	0000	0000	0000
			↓						
PY	1120	2000	0010	0200					

In 1902, pyritic process (PY) is tested. It's **autogenous**, but limited by lack of suitable ores.

Development of flash smelting

BF	1100	2000	0010	0200	R	0000	0000	0000	0000
		↓					↓		
PY	1120	2000	0010	0200	R1930	0000	0001	0001	0110

E1930 0010 0110 1101 0000

In the 1930s, electric furnaces (E1930) spread (incl. Imatra), and reverberatories are improved.

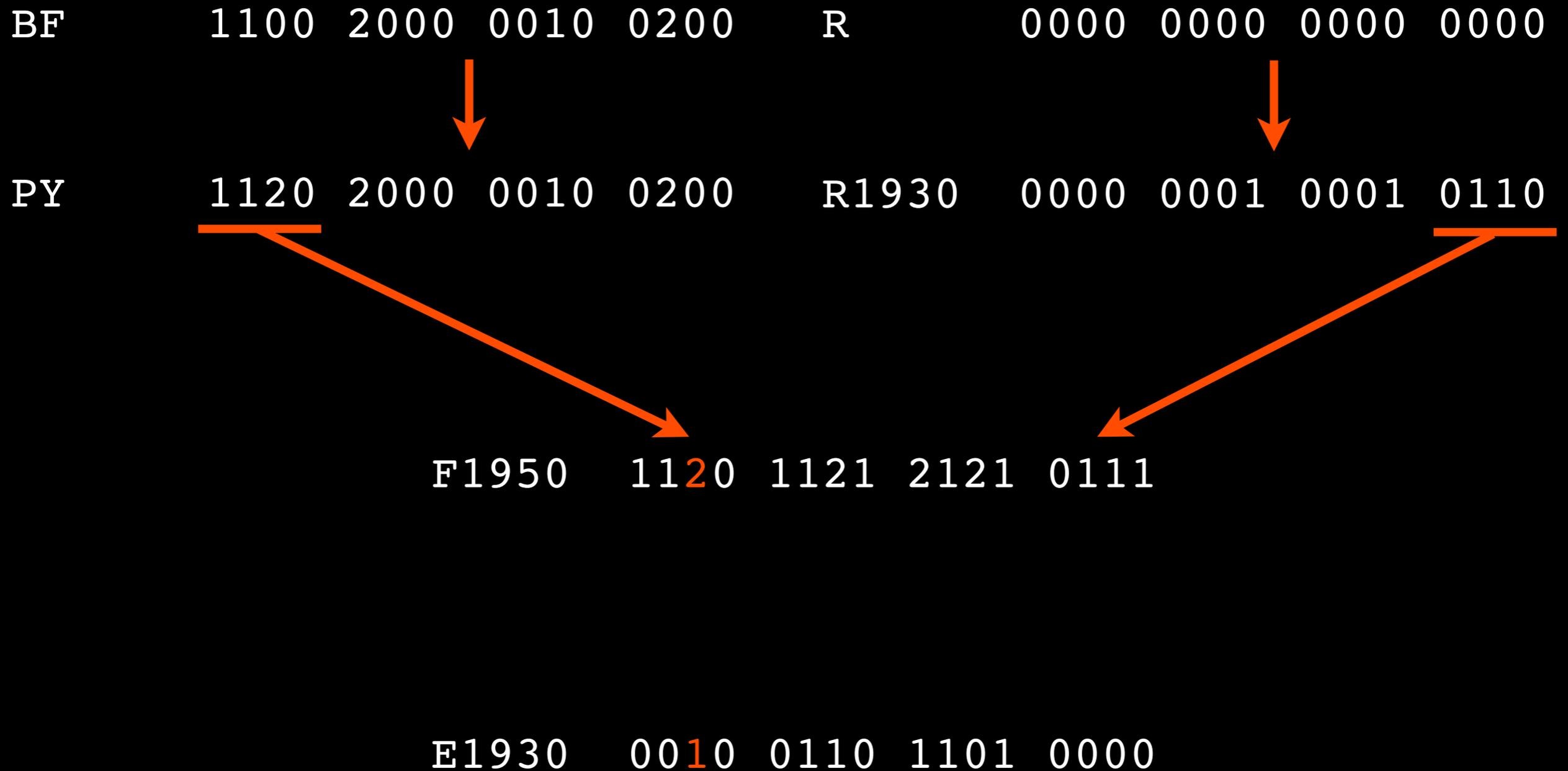
Development of flash smelting

BF	1100	2000	0010	0200	R	0000	0000	0000	0000
		↓					↓		
PY	1120	2000	0010	0200	R1930	0000	0001	0001	0110

E1930 0010 0110 1101 0000

Electricity shortage after WW2 focuses search for alternative sources of smelting energy.

Development of flash smelting



First flash furnace in 1949; integrates roasting, uses concepts proven in fluid bed reactors.

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Search & *constraints*:

The effect of constraints: focuses search on improving attributes that are affected by scarcity.

Constraints act as a *focusing device* (Rosenberg 1969); focusing search to certain attributes.

This is known as *function space search* after Bradshaw (1992) and Frenken (2001).

Measuring differences

When artefacts (or systems) are coded as strings, measuring their differences is easy!

Hamming distance measures the differences between two solutions:

Measuring differences

BF 1100 2000 0010 0200

R 0000 0000 0000 0000



PY 1120 2000 0010 0200

R1930 0000 0001 0001 0110

Hamming distance 1

Hamming distance 4

Measuring *innovation*

BF 1100 2000 0010 0200



PY 1120 2000 0010 0200



F1950 1120 1121 2121 0111

Hamming distance 11

Hamming distance can be used e.g. to measure radicalness of innovation, creativity, novelty...

Epistasy, *revisited*

	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9
W_1									
W_2									
W_3									
W_4									
W_5									
W_6									
W_7									
W_8									
W_9									

Epistasy, *revisited*

	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9
W_1	X								X
W_2	X	X							
W_3		X	X						
W_4			X	X					
W_5				X	X				
W_6					X	X			
W_7						X	X		
W_8							X	X	
W_9								X	X

Why e.g. distributed teams work

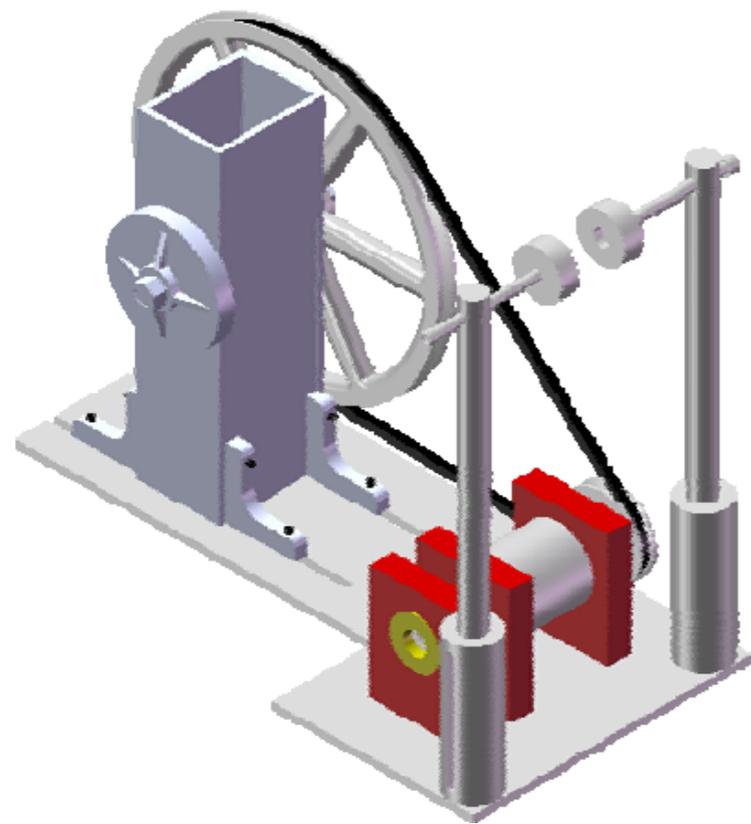
	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9
W_1	X	X	X						
W_2	X	X	X						
W_3	X	X	X						
W_4				X	X	X			
W_5				X	X	X			
W_6				X	X	X			
W_7							X	X	X
W_8							X	X	X
W_9							X	X	X

Near-decomposable:

	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9
W_1	X	X	X						
W_2	X	X	X						
W_3	X	X	X						
W_4			X	X	X	X			
W_5				X	X	X			
W_6				X	X	X			
W_7						X	X	X	X
W_8							X	X	X
W_9							X	X	X

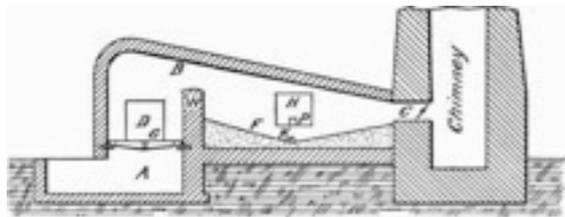
Most real life problems are nearly decomposable - they can be solved in parallel

Low epistasy technology

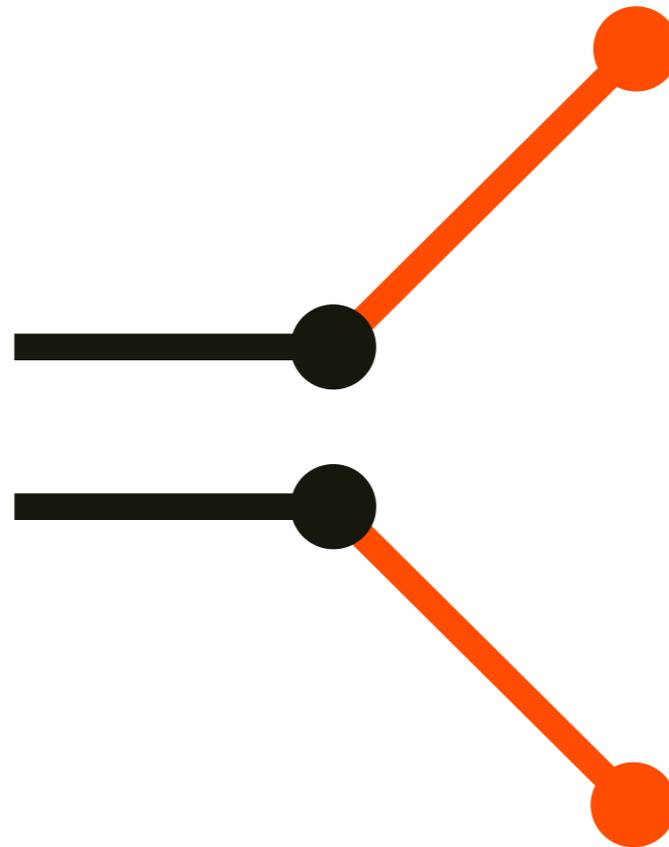
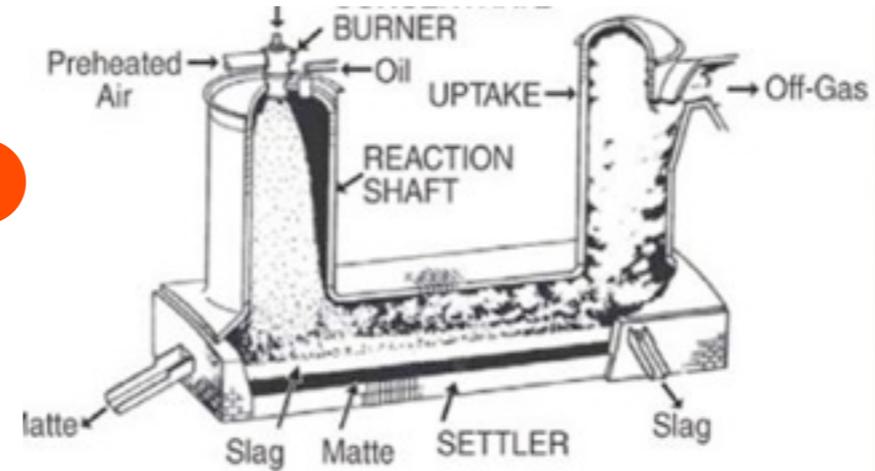
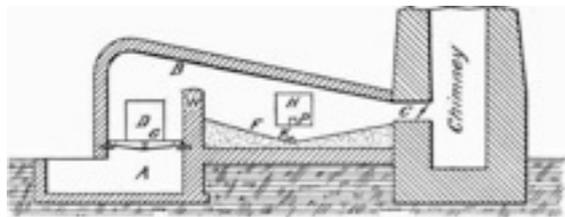


Technologies developed for use in the developing world tend to be highly modular to accommodate variety in components, *i.e. they are near/fully decomposable*, such as this bicycle-powered grain crusher

The effects of *scarcity* (?)

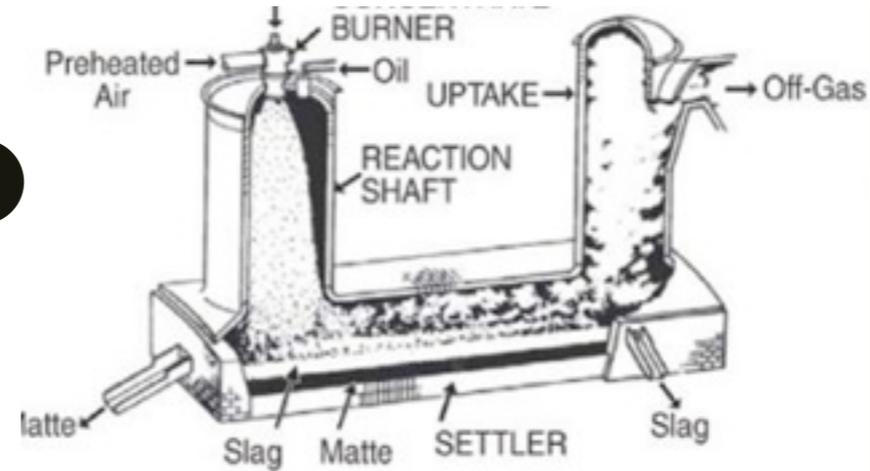
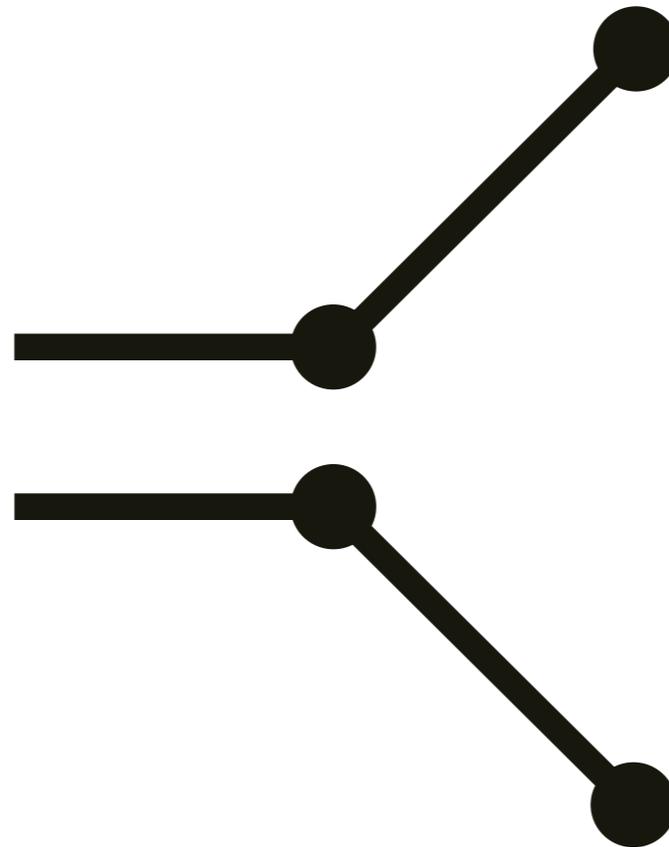
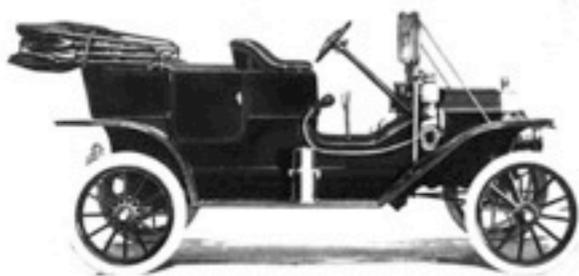
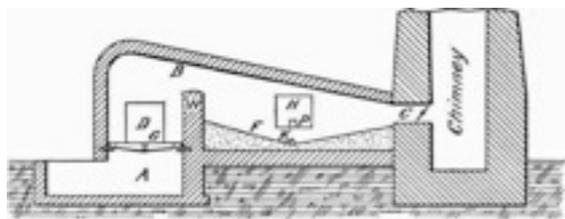


The effects of *scarcity* (?)



Alternative energy solutions are found.

The effects of *scarcity* (?)



Integration
(\approx epistasy)



However, wood gas was not an integrated, efficient system - flash smelting was.

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Other implications...

The theories used here are applicable to a large variety of complex systems, and have interesting implications, e.g.

- Systems with *moderate complexity* have the highest fitness (Schilling 2000)
- The more complex a problem is, the more solutions differ from each other (Kauffman 1993)
- The *speed of evolution* is inversely related to the complexity of system's architecture (Kauffman 1993)
- *Imitation strategies* are less successful, the more complex the system being imitated is (Rivkin 2000)
- *S-curves* are easy to explain: local/global optima!

Computing organizations

“Computational organization theory?” Based on theory of computation, organizations as *computational systems* (e.g. Saraceno and Barr 2002; also Wolfram 2002; Sipser 2006)

e.g. showing the limits of theory: *the fastest way to determine what an organization will do is to let the organization do it; thus,*

“shortcuts” (=theories) are limited, thus,

the predictive power of our theories is inherently limited. □

One more thing...

The question “why we have so much variety” is *much less interesting* than the question

why the lack of variety?

Current variety?

How many organizational forms there are in ≤ 50 person firms today?

Possible variety?

Exercise: how many different organizational forms could a 1-50 person company have, if there are just three levels in hierarchy?

e.g. possible positions are 1) top management, 2) middle management, 3) worker?

1.077 x 10²⁴

If you started at the Big Bang (\approx 13,8 billion years ago), you'd have to go through

2 500 000

solutions *per second* to find all the possible combinations

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