Technology and Combinatorial Evolution

CSSS 2016

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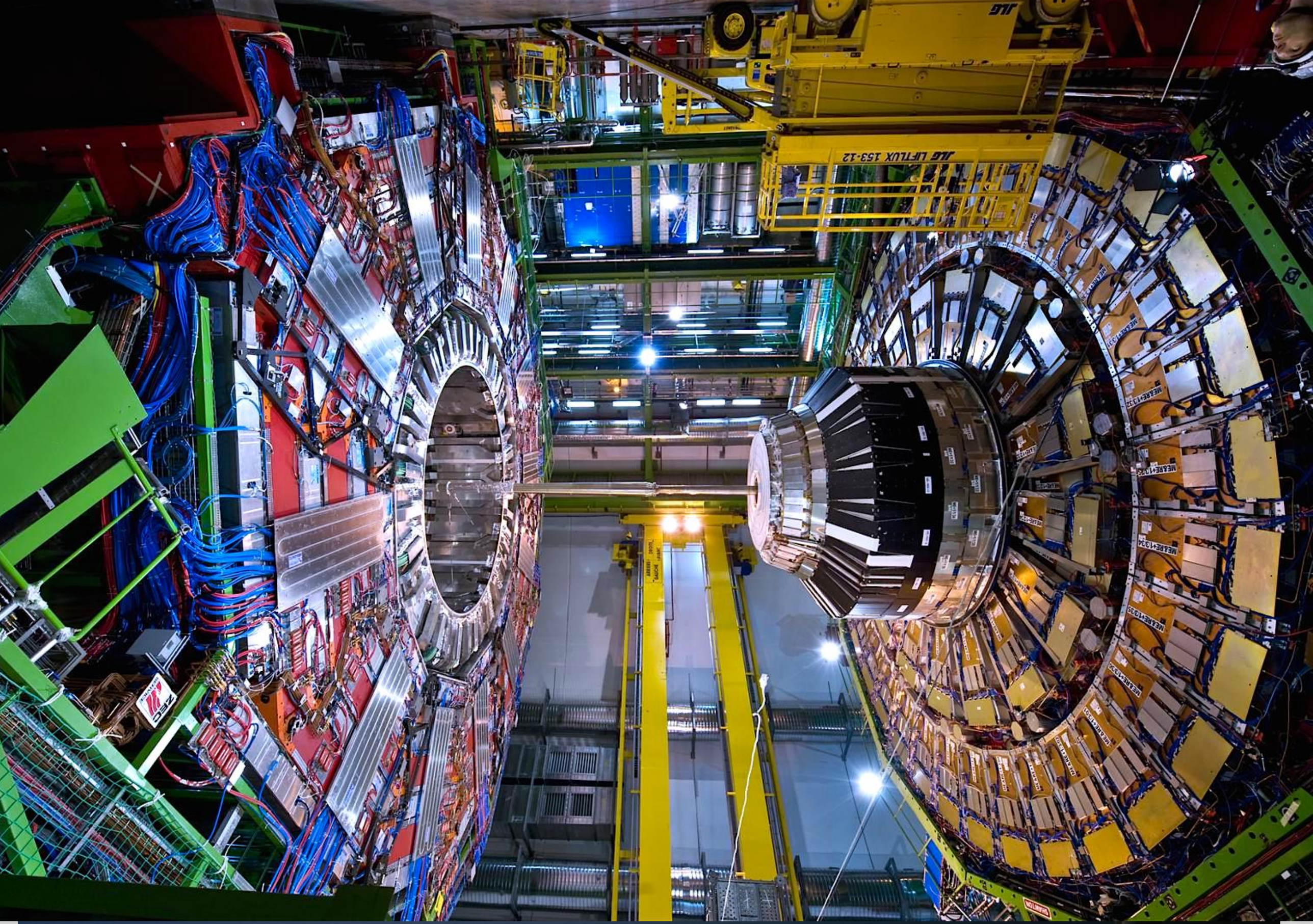
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A puzzle: How does technology evolve over time?

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Evolution's two meanings:

Lineages alter their form – descent by modification

All organisms are related by ties of genealogy or descent from common ancestry

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Darwin's Mechanism

"It is the steady accumulation through natural selection of such differences, that gives rise to all the important modifications of structure."

"Complex organs … formed by numerous, successive, slight modifications"

Problem: Doesn't work for technology

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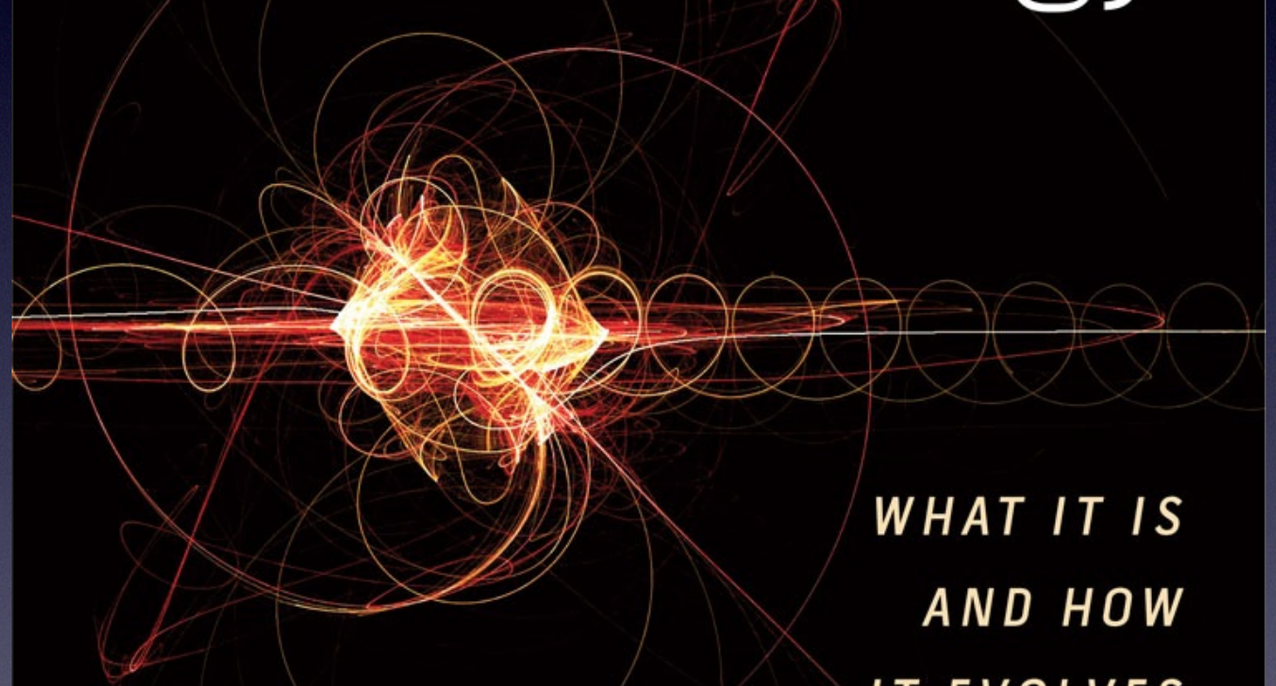
The Nature of Technology



WHAT IT IS
AND HOW
IT EVOLVES

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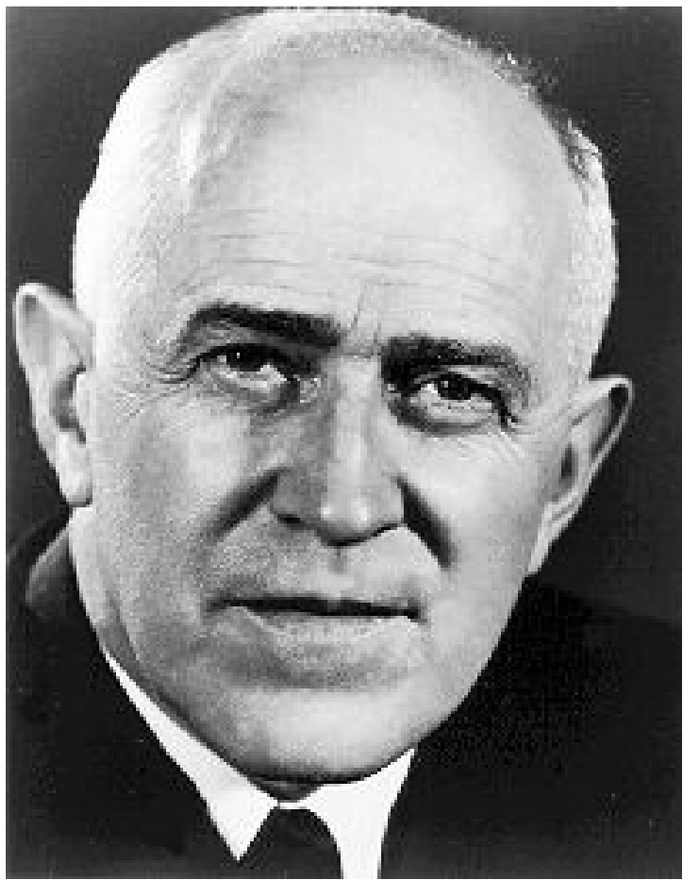
A hint: Ogburn's Claim (1922)



William Fielding Ogburn
Social Change, 1922

"It would seem that the larger the equipment of material culture, the greater the number of inventions. The more there is to invent with, the greater will be the number of inventions. When the existing material culture is small, embracing a stone technique and a knowledge of skins and some woodwork, the number of inventions is more limited than when the culture consists of a knowledge of a variety of metals and chemicals and the use of steam, electricity, and various mechanical principles such as the screw, the wheel, the lever, the piston, belts, pulleys, etc. The street car could not have been invented from the material culture existing at the last glacial period. The discovery of the power of steam and the mechanical technology existing at the time made possible a large number of inventions."

Two observations

All novel technologies are "solutions" to some problem

All such solutions are put together from parts that exist or can be made to exist

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In other words

Technologies are constructed … from existing technologies

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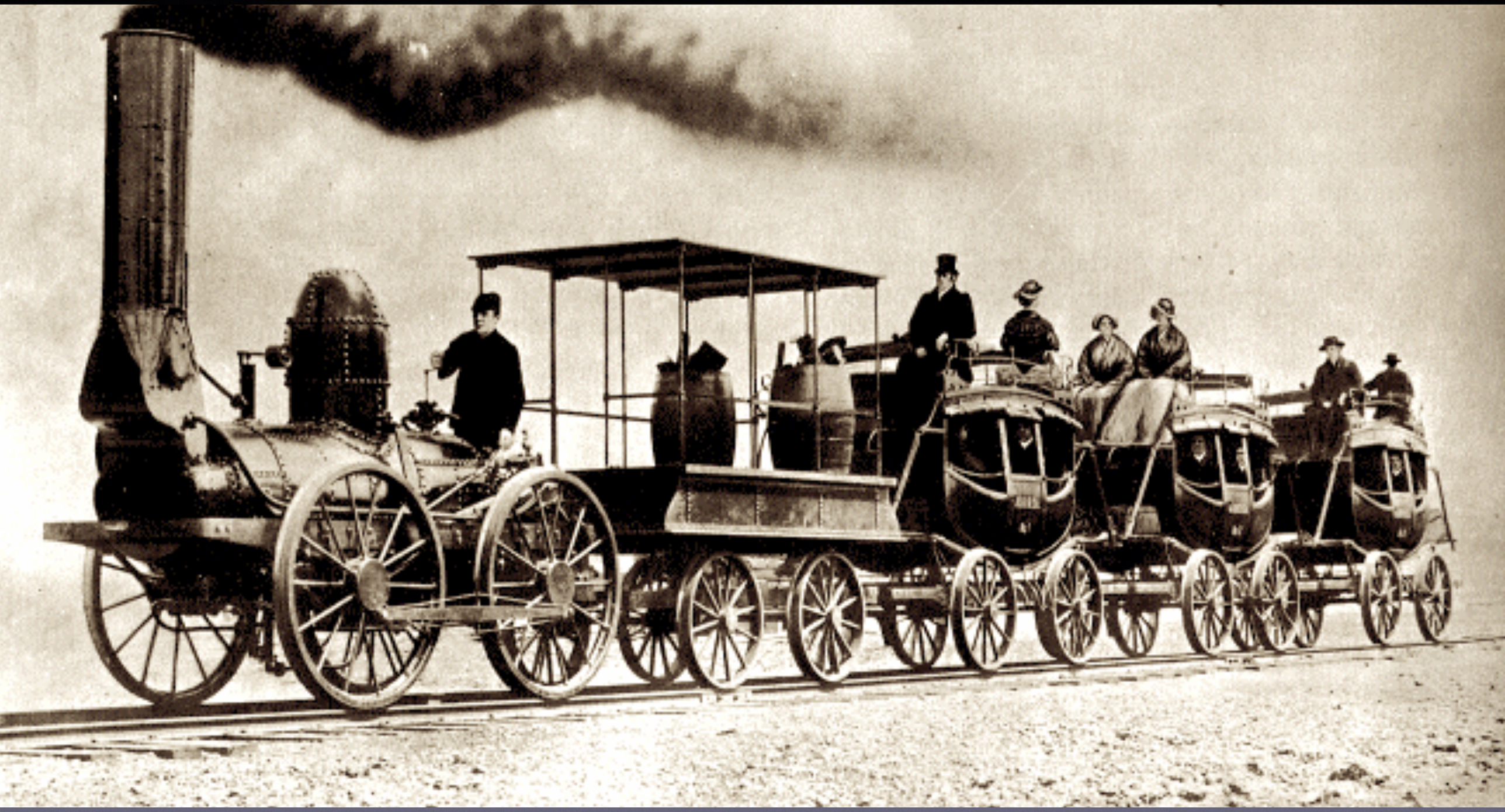
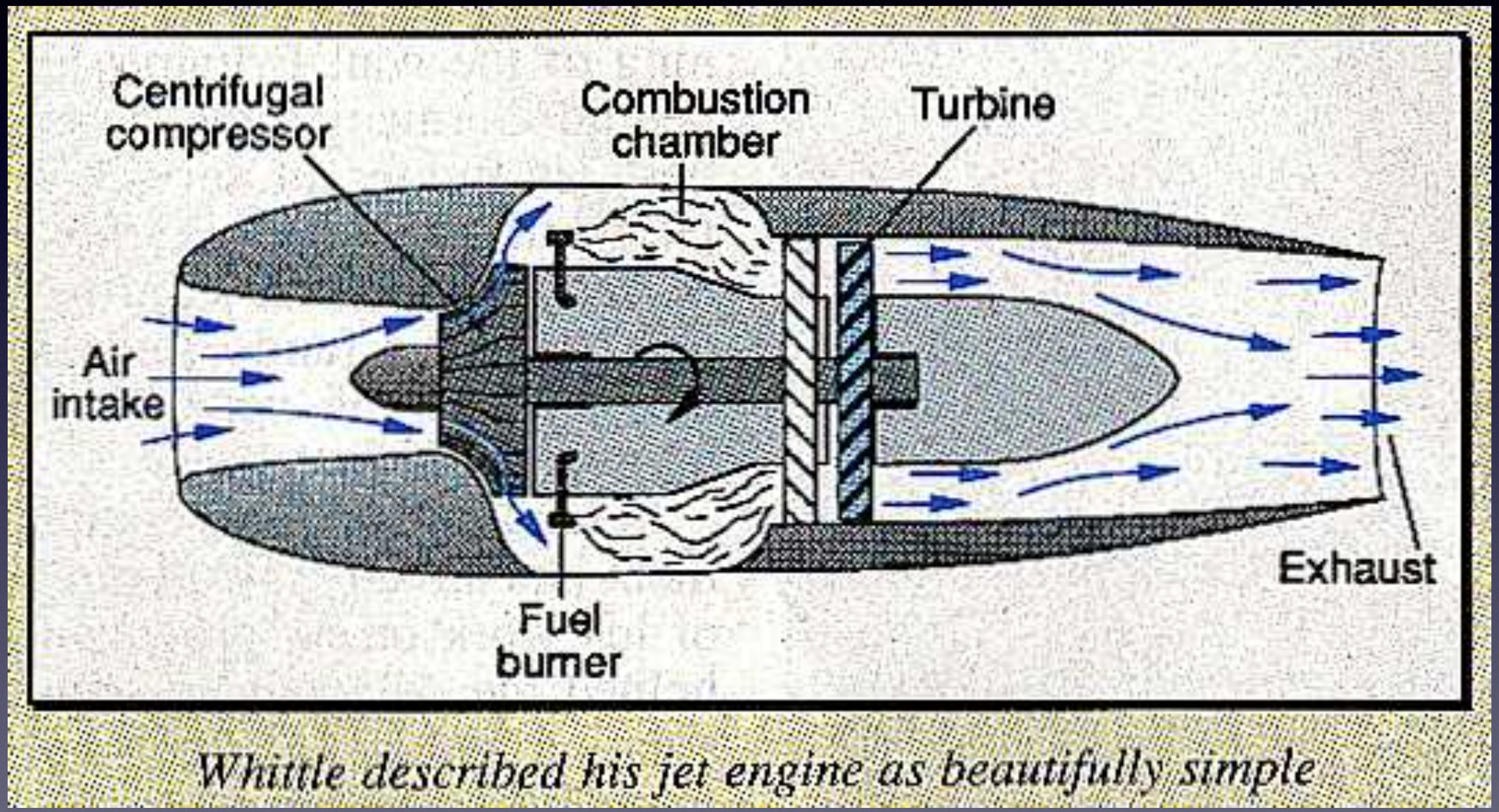


Jet engine



Whittle described his jet engine as beautifully simple

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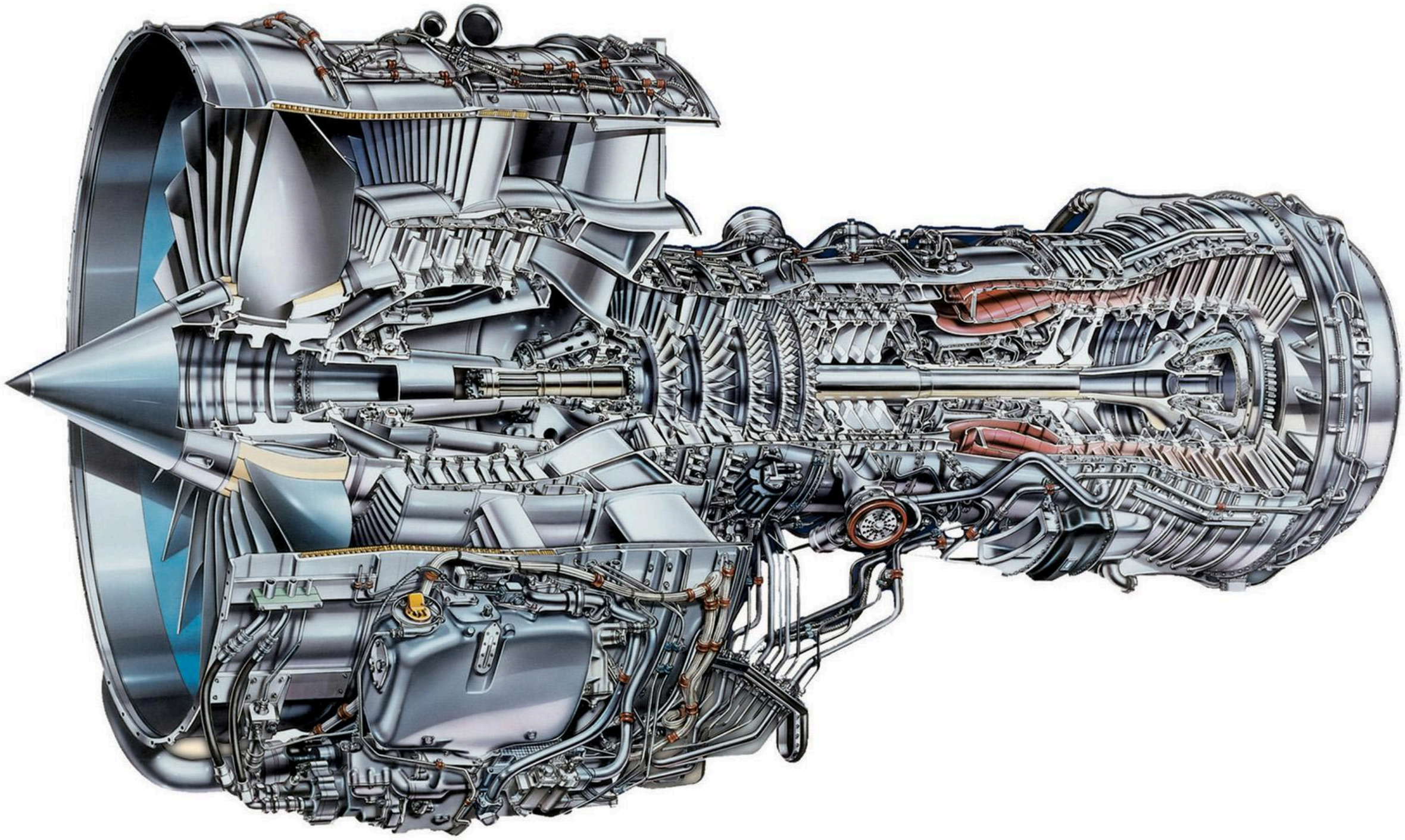

Actual invention is complicated

Invention is basically problem solving using existing "parts" and solving the sub-problems created, recursively

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Example: Gary Starkweather 1972

Problem: How to print images from a computer

Several possible principles

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Gary Starkweather's problem 1972

Possible principle: Use a laser to "paint" images on a Xerox drum

Sub-problems:

Modulating the laser

Moving the laser rapidly

- Use a mirror

Problem of lining up the mirror facets

- Solve this optically

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From Computer Desktop Encyclopedia
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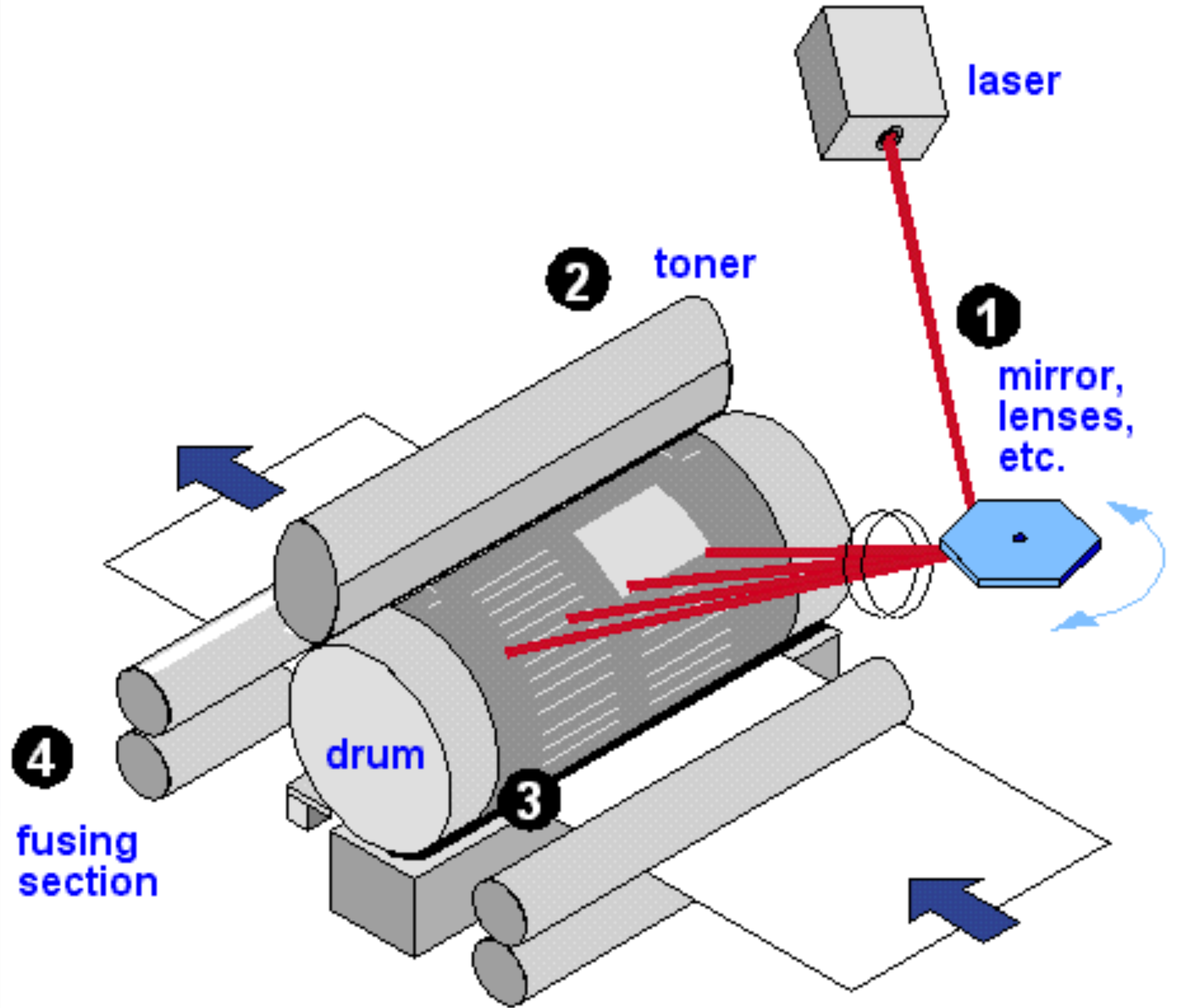

So we can say …

Novel technologies are constructed from existing technologies …

These offer themselves as components—building blocks—for the construction of further technologies

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Technology and Evolution

1. Technology is a set of elements
2. Which in combination create new elements
3. Which form niches for the appearance of yet further elements
4. The whole evolves over time

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Is there a general mechanism here?

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François Jacob

"In our universe, matter is arranged in a *hierarchy of structures by successive integrations.* Whether inanimate or living, the objects found on earth are always organizations or systems. *Each system at a given level uses as its ingredients some systems from the simpler level.*

… The great diversity of vertebrates results from differences in the arrangement, in the number and distribution, of these few [building blocks]."

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Combinatorial Evolution

May have a "chemistry" of elements some of which

In combination give rise to further elements

Some form building blocks for creation of further elements

The whole forms an ecology that calls forth further elements

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This suggests an evolutionary algorithm

1. Start with a "soup" of elements
2. Form combinations (possibly at random) from this
3. If a combination is useful, encapsulate and preserve it
4. Add new combination to soup as a building block element

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Can we show this mechanism

of evolution in practice?

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An Experiment at FujiXerox Palo Alto Lab

W. Brian Arthur and Wolfgang Polak (Complexity, 11, 5, 2006)

Idea

- Create an artificial world in which the technologies are logic circuits
- Allow the system to create technologies by combining previous technologies and evolve new ones

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An artificial world within the machine

- Little agents in green eye shades
- They have a wish list of "needs" for logic circuits to be potentially fulfilled

(2-bit Exor, 4-bit Equals, 2-bit adder, etc)

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How the experiment works

1. Start from one primitive element (a NAND gate)

2. Make circuits by random combination of existing elements

3. Check to see if any needs (target logic purposes) are fulfilled

4. If so, these novel circuits become new building blocks

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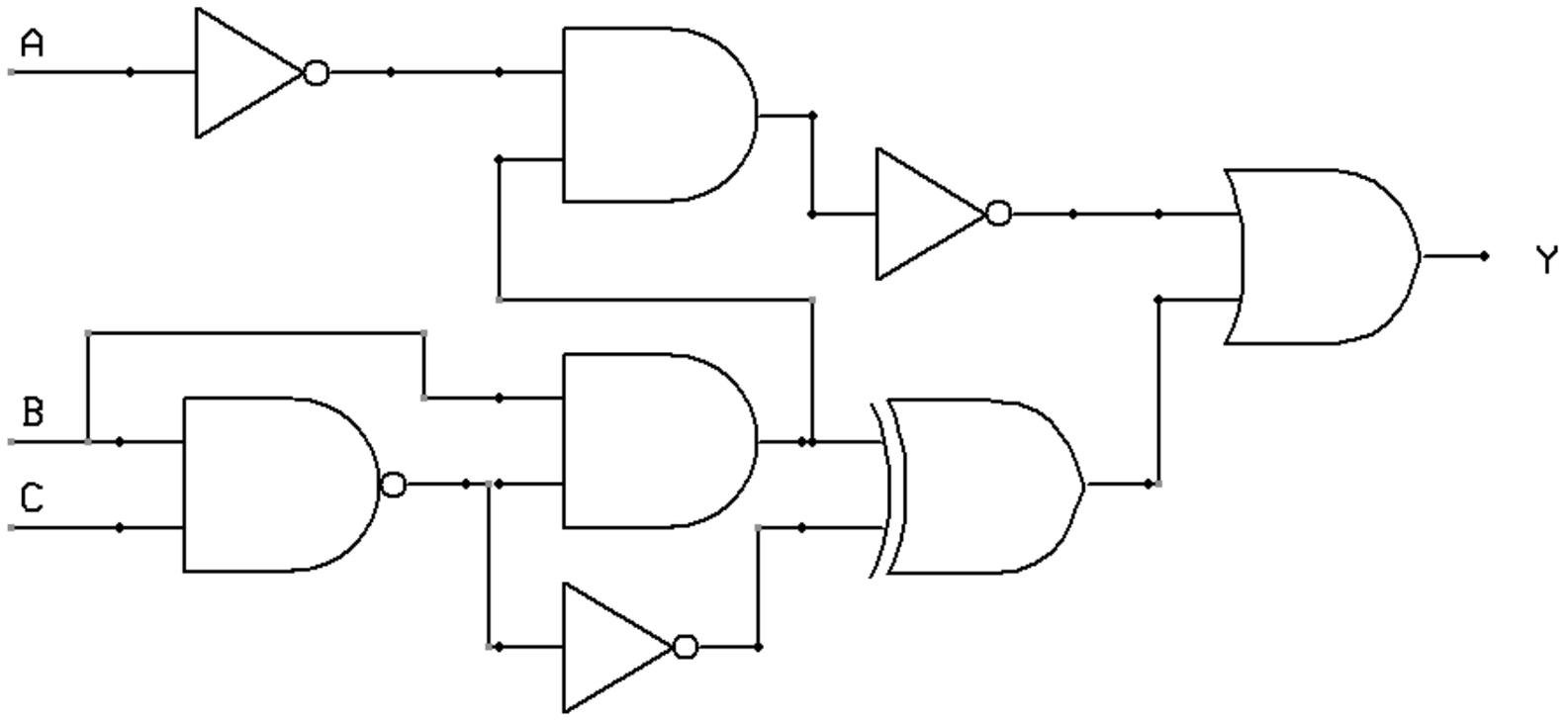
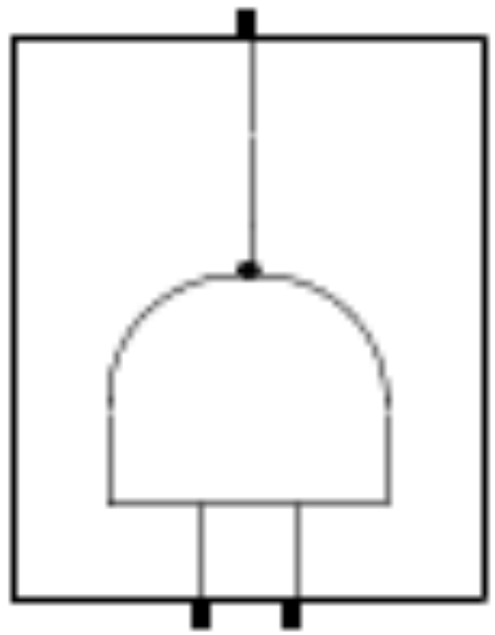
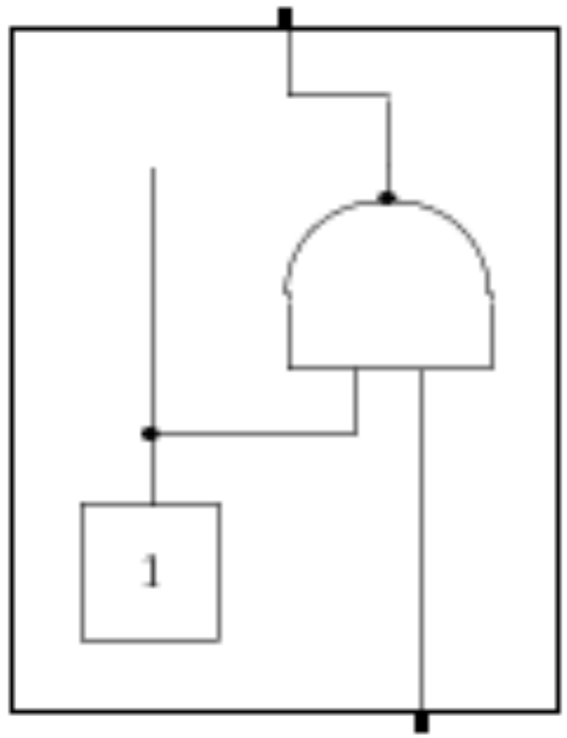
A	B	C	Y
0	0	0	
0	0	1	
0	1	0	
0	1	1	
1	0	0	
1	0	1	
1	1	0	
1	1	1	



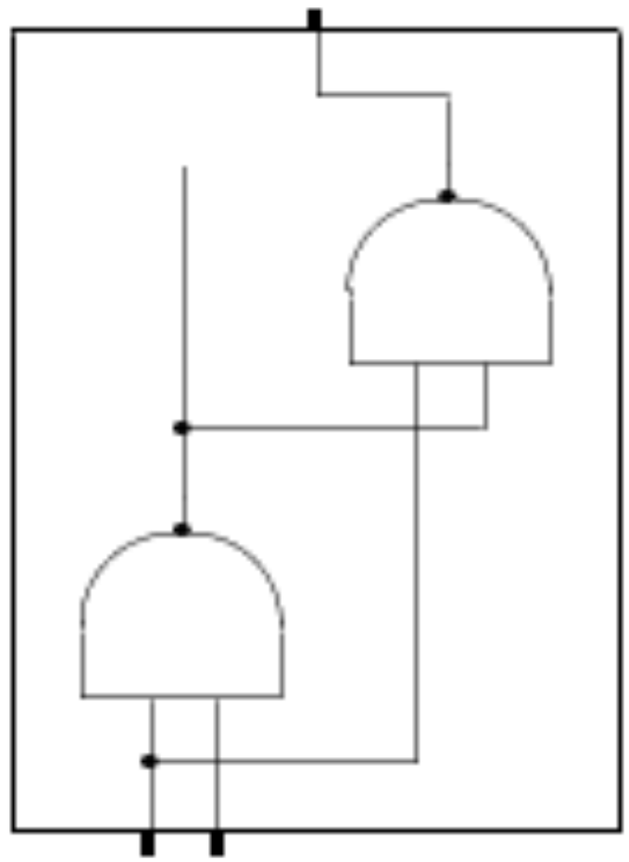
Typical logic circuit



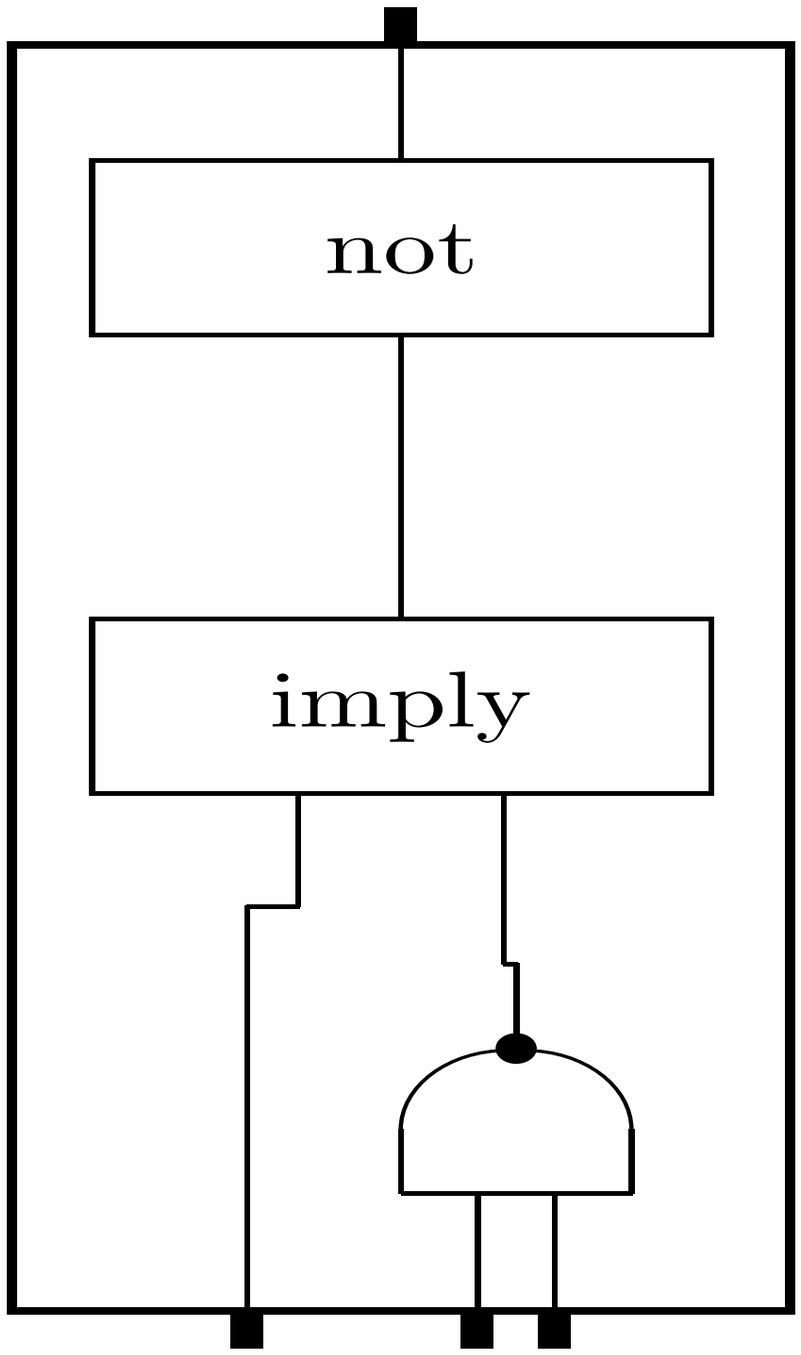
NAND:
the primitive element



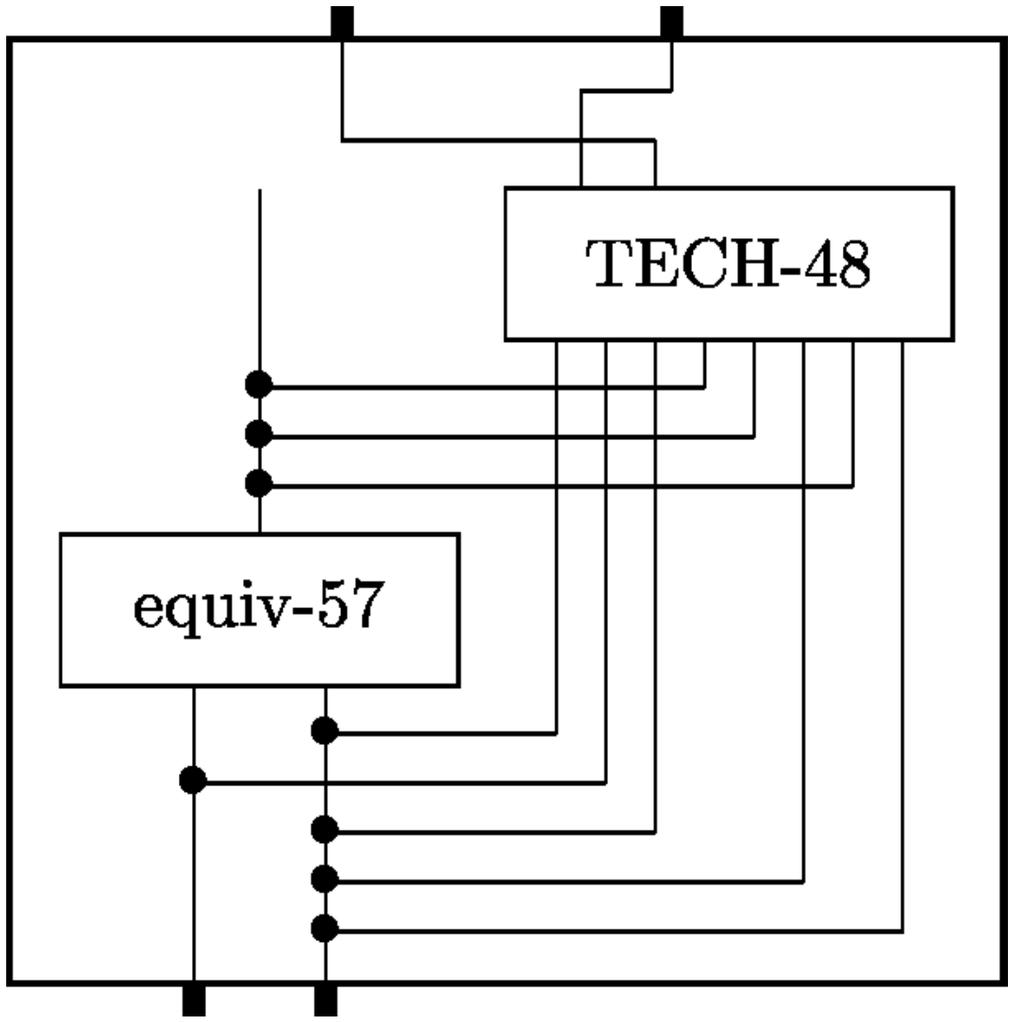
NOT circuit



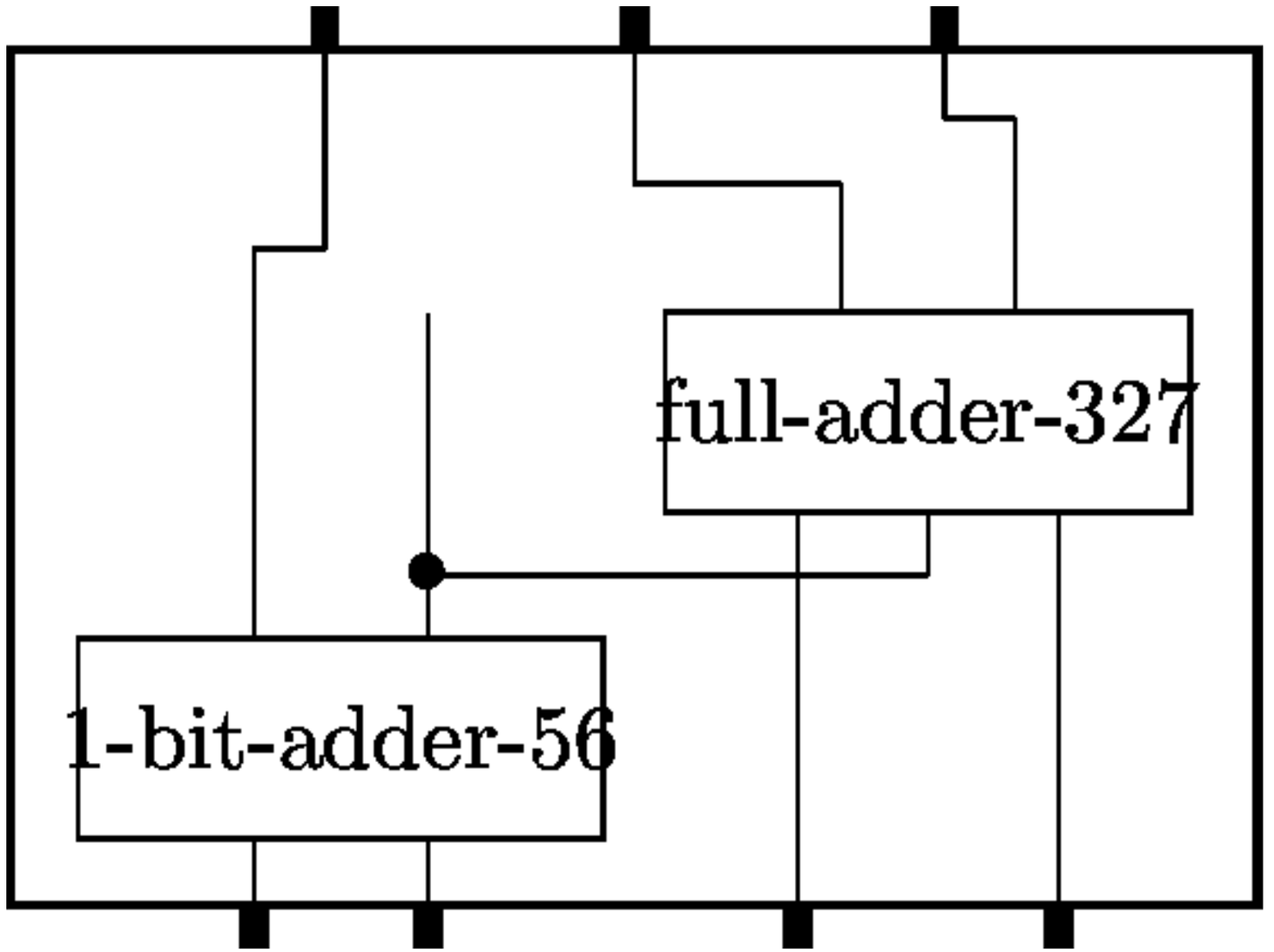
IMPLY circuit



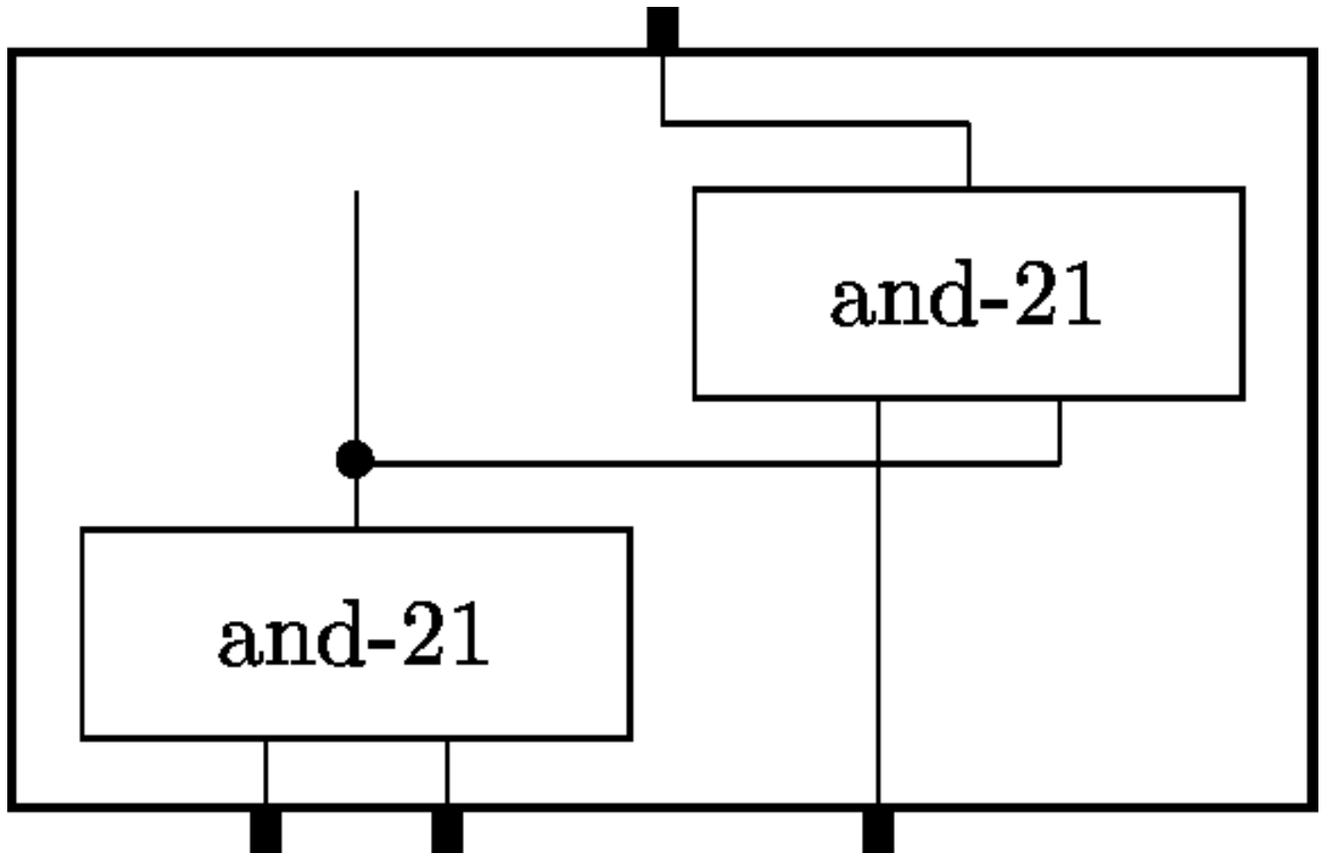
3-bit AND



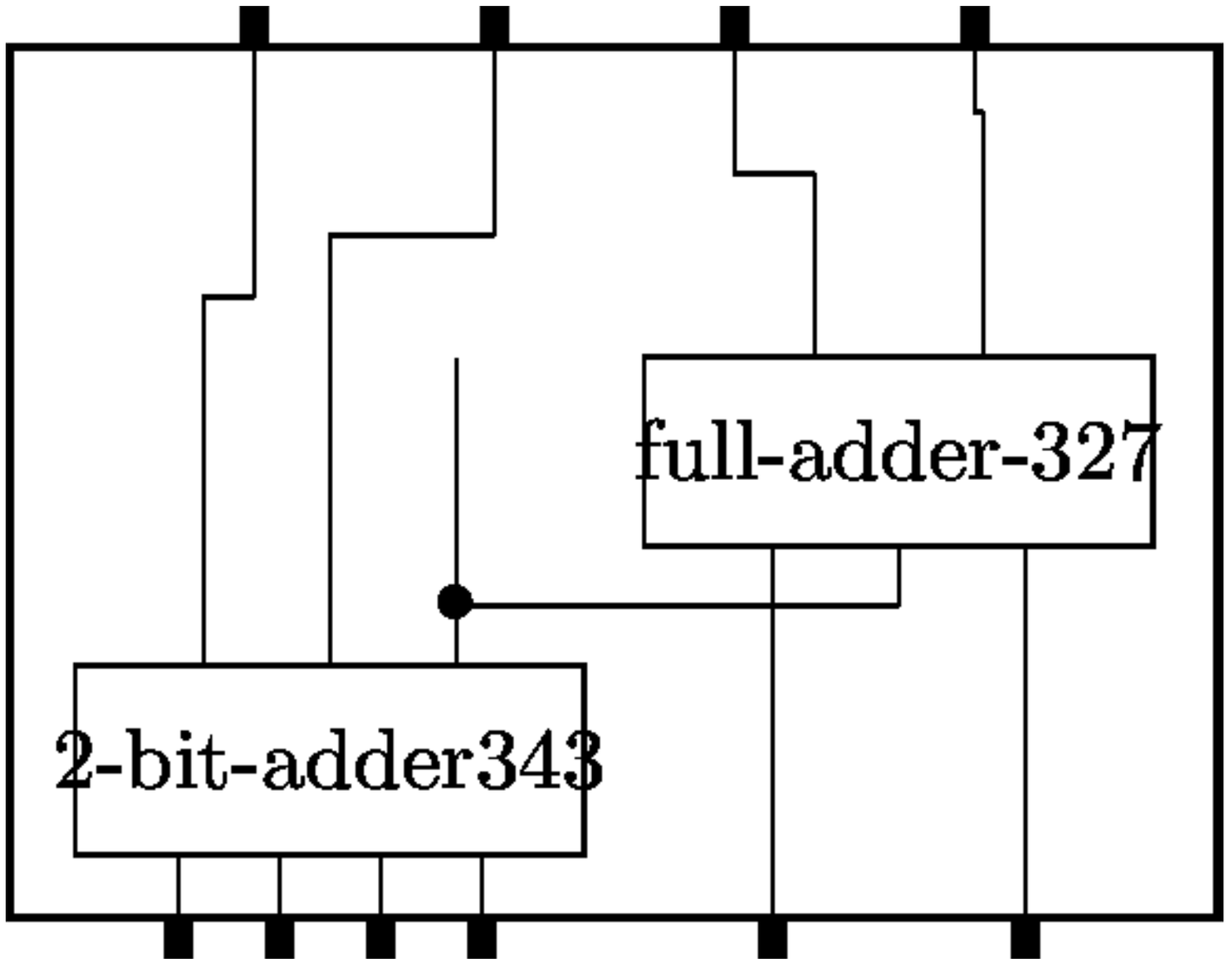
1-bit adder



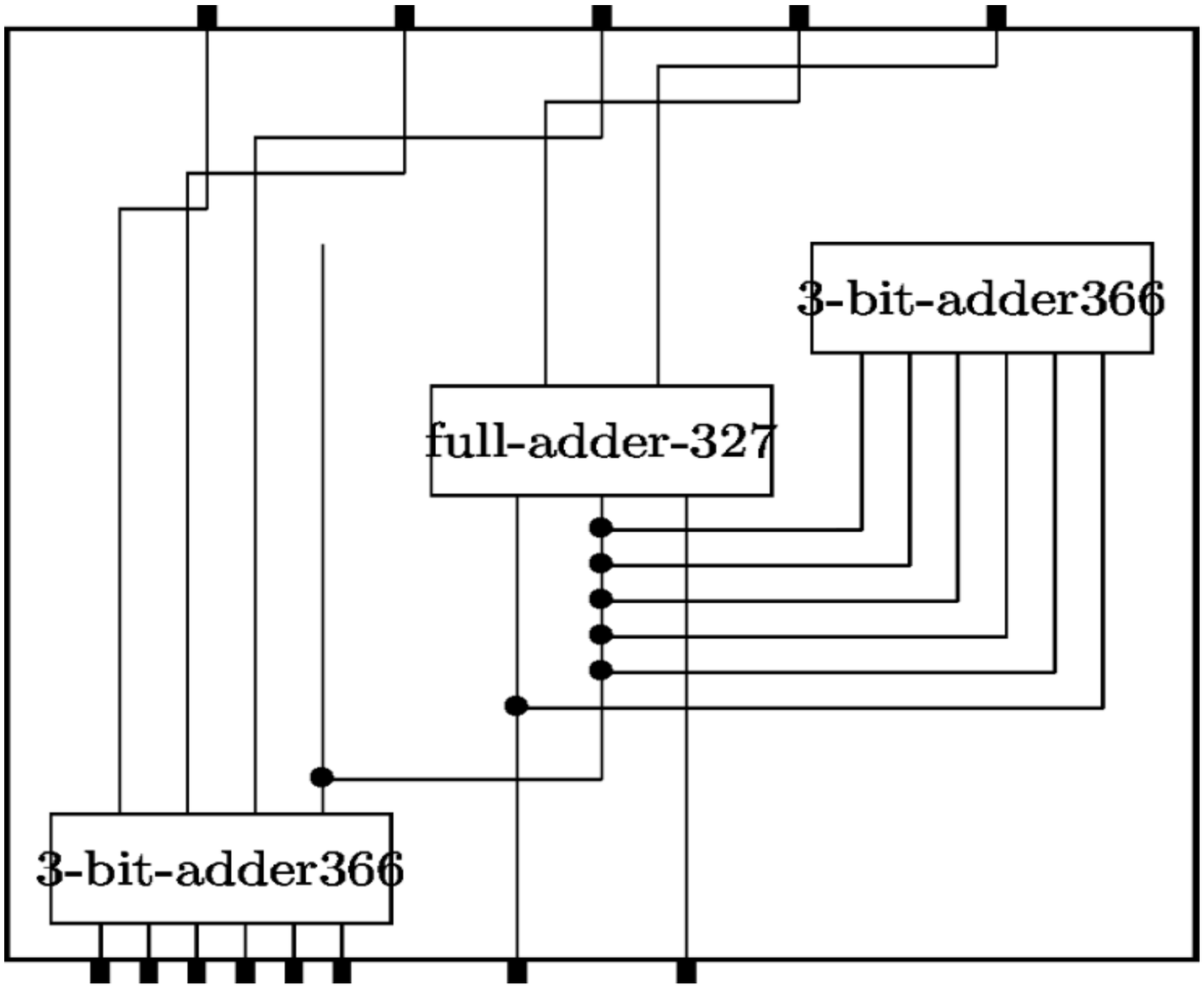
2-bit adder



Tech 33: And-3



3-bit adder



4-bit adder

After 250,000 steps

1. Quite complicated circuits have evolved:
   - 8-way EXOR, 8-way AND, 4-bit EQUALS, 3-bit-LESS, 8-way OR, 8-bit adder, etc.
   - An 8-bit adder (16 inputs, 9 outputs). This is one of $10^{177,554}$ possible circuits

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But these complicated technologies require

intermediate steps

They require intermediate (simpler) technologies
… which only appear if there are intermediate needs

(Cf. R. Lenski et al. Evol. Origin of Complex Features)

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A Cambrian explosion

After about 30,000 steps, sudden appearance of key circuits (enabling technologies) then quick use of these

– Full adder appears after 32,000 steps; 2,3,4-bit adders

quickly after that

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The evolution is history dependent

New technologies build out of ones "discovered" earlier

So the order in which techs are invented matters

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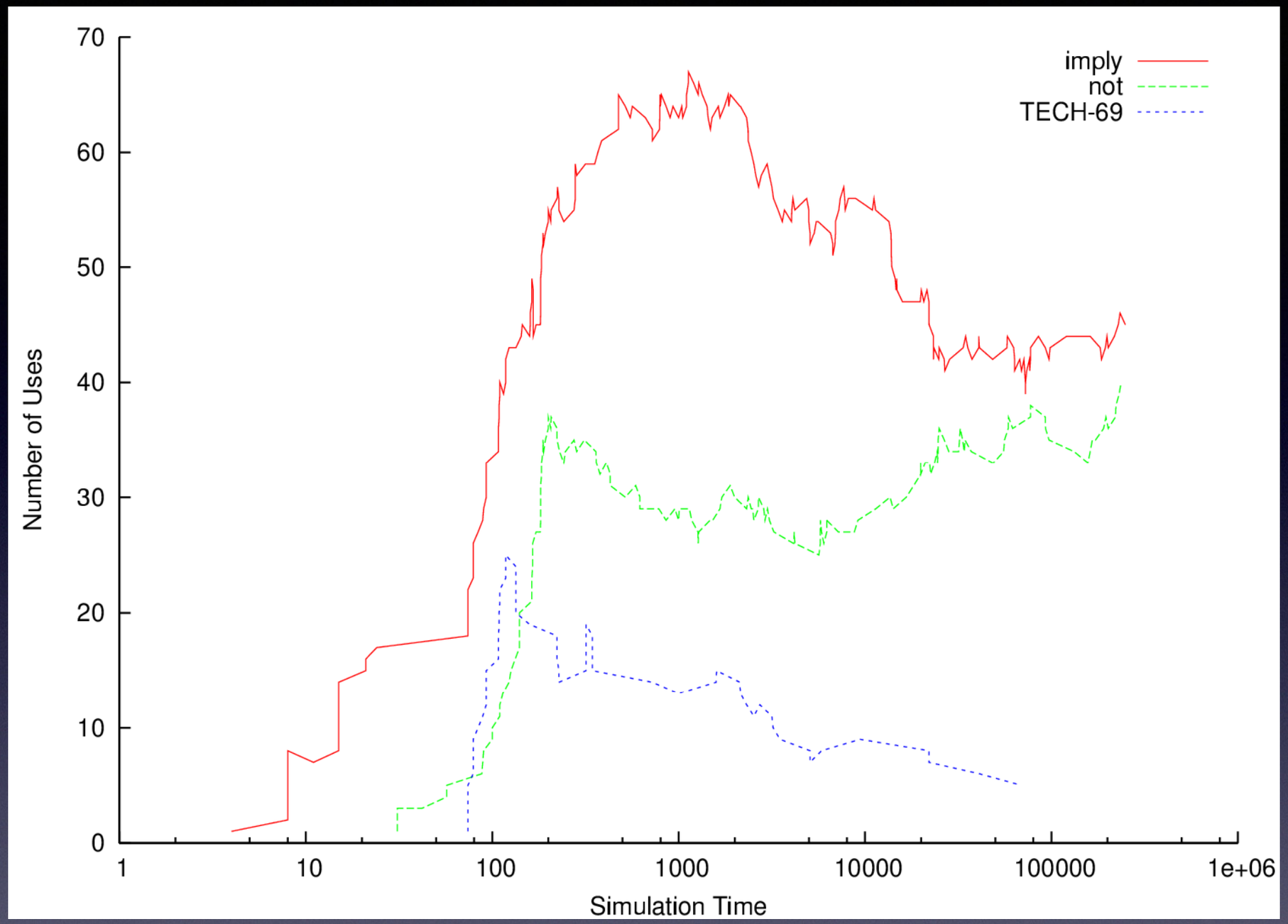

Figure 5: `Implication`, being invented before `negation` in this example, is used more heavily. Usage declines over time as better technologies are invented.

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Schumpeter's Gales of Destruction

When a technology disappears (is replaced) a technology it used may have no further use. That tech then disappears

…. etc.

Q. Are these gales "sand-pile avalanches"?

–I.e. is the system at self-organized criticality?

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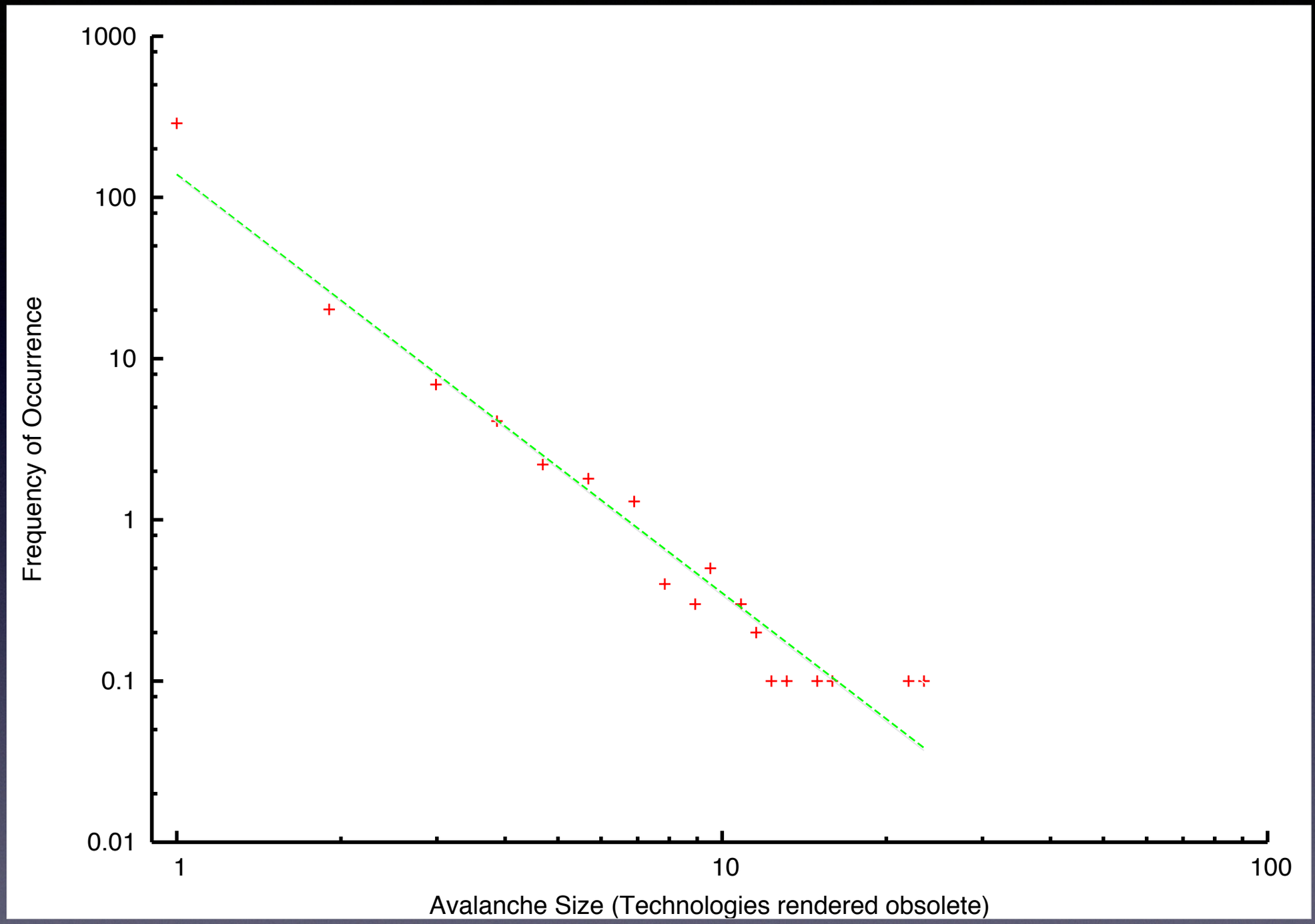

Avalanches of destruction follow a power law

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Biological vs. Technological Evolution

Biological:

- Darwinian variation and selection,
- accumulation of incremental changes
- Combination occurs too

Technological:

- Combinatorial, abrupt, encapsulates
- self-augmenting
- Much Darwinian evolution once a technology exists

How general is this mechanism of combinatorial evolution?

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Combinatorial Evolution occurs in:

All chemistries

(Computer) library functions

Mathematics

Genetic regulatory networks

Physical cosmos

The major transitions in biology

Synthetic biology, Etc.

What has this got to do with complexity?

Most complex system studies assume fixed elements

We should study complex systems in which new elements form from previous ones, and form an ecology that calls forth the formation of further new elements

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Conclude

A theory of evolution for technology is possible

Combinatorial evolution mechanism is widespread

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