Viewpoint

- Beyond Heroes and Mythology
- What Worked, What Didn’t, and Why.
- (For Business)
- For Public Policy
A Very Simple Policy Model

The Commissar Model: \((v - c) > 0\)

Choosing Incentives to Get There

“No dominant incentive mechanism.”
A History of \((v - c)\) to 1970:

A History of “v.”
Technology improves.
Society uses more data.
Inventors notice existing uses.

A History of “c.”
Spreading R&D costs over bigger markets.
Gears, vacuum tubes
Integrated circuits and software.
Lecture 1: Computing to 1940
Prehistory: Data & Civilization
An honest man has hardly need to count more than his ten fingers, or, in extreme cases, he may add his toes and lump the rest. I say, let our affairs be as two or three, and not as a hundred or a thousand; instead of a million count half a dozen, and keep your accounts on your thumbnail.”

- Henry David Thoreau
Prehistory

Data for Governance

- Irrigation Cultures (ca. 3000 BC)
- Egypt (ca. 1500 BC)
- Roman Imperial Household (1st Century AD)

The “v” in (v - c).
Data for the Military

- Military paybooks (1500 BC)
- Philip II (382 – 286 BC)
  and Alexander (356 – 323 BC)
- Ptolemy I (d. 246 BC)
Data for Research

- Aristotle (384 – 322 BC)
  ~ 400 books
- Library of Alexandria (283 BC)
  750,000 papyri
Collapse:

Dark Ages (AD 476 – 1000)
Medieval Life
Renaissance (14th – 16th Centuries AD)
Warfare & Commerce
Reemergence

Commerce, States, Empires

Philip II (1527 – 1598)
18 hour workdays
Inbox: 2000 pp./day
Outbox: 300 memos/day.

Thirty Years’ War (1618 – 1648)
Gustavus Adolfus (1594 – 1632).
And something new: Big Science Problems

Tycho Brahe (1546 – 1601)
Computing Trig Functions

Wilhelm Schickard (1623 – 24)
Professor of Mathematics, Astronomy and Hebrew
Designed machine for Kepler
that could add, subtract, multiply, and divide.

Source: http://www.gris.uni-tuebingen.de/projects/schickard/index.html
Origins:
17th – 18th Centuries
Blaise Pascal (1623 – 62)
Mathematical Prodigy
Wheelbarrow
Hydraulic Press
Barometer
Probability Theory
Etienne Pascal’s Tax Headache

Prototype (1642) & Patent (1645)
Adding and Subtracting
Business Plan

Demonstrations & Financing
50 “Pascalines” built through 1652
Cost: 100 livres each.

Slow, temperamental.
Gottfried Leibnitz (1643 – 1716)

Concept: 1671
Definitive Machine: 1694
Goal: “It is unworthy of excellent men to lose hours like slaves in the labor of calculation, which could easily be passed on to anyone else if machines were used.”

Incentives: Aide to Elector-Archbishop of Maintz
Why Didn’t It Work?

Technology
Gears: Tolerances, Slack and Binding.
Performance Inadequate?
A Circular Argument?

Economics
Spreading R&D Costs
Was the Market Big Enough?
How Much Computing Did the World Need?
19th Century Sequel

Thomas de Colmar (1820)
  Arithmometer
  7 figure accuracy, $150 each.
  Engineers and insurance companies.

Rise of Big Business:
  Nabisco (1893), Travelers Insurance (1883),
  Firemen’s Fund (1863), Alcoa (1888)

Dorr E. Felt (1887)
  Keyboard
  Comptometer
William S. Burroughs
Burroughs Adding Machine Company, later Unysis

Printing calculators
Sold to banks and clearing houses at $220 each.
1,000 machines/year by 1900.
130,000 machines/year by 1908.
58 Models, “One Built for Every Line of Business”

Success: Improved technology base.
Market penetration is (reasonably) fast.
R&D can now be spread over huge markets.

A Robust Technology
The Manhattan Project
A Success Story for Patents?

Determining private needs.
But: \((v - c)\) for very expensive inventions.
But: \(ex\ ante\ vs.\ ex\ post\) efficiency.
But: Government as buyer?
But: Financing and information asymmetry.
19th Century: The Idea of Computers
From Automata to Weaving

Pre-History
Myth: Haepehestus, Golem, Albertus Magnus
Library of Alexandria
Medieval Clocks
Leonardo DaVinci (1452-1519)
Julian Turianno (ca. 1556)
Hans Bullman (ca. 1547)
Rene Descartes & “Soulless Machinery”
Basil Bouchon
Punched Cards (1785)

De Vaucanson (1709 – 82)
Automata
Director of State Silk Mills (1741)
Joseph Marie Jacquard (1752 – 1834)

Fishing net machine – Prize and patent
Pattern Loom (1806) – Prize + Royalty
Lyons Riots (1810)
11,000 looms in operation by 1812
Serendipity: Playthings turn out to be useful
  Patents won’t work - Patronage and reputation
  Lead users?

Late Stage Innovation
  Patents vs. Prizes
Charles Babbage
Charles Babbage (1792 – 1871)
Banking/Establishment roots
Obsessions: Automata, Mistakes, Street Musicians.

Other Projects
Chess Player
Penny Post
Actuarial tables
Speedometer
Cowcatcher
Physics, Geology, Mathematics
Lucasian Professor of Mathematics (Cambridge)

Ada, Countess of Lovelace (1815 – 52)
Difference Engine
Difference Engine
Errors in Tables
Firing and Navigation Tables
Gaspard de Prony (1755-1839)
## Method of Differences

Thomas Harriot (1560-1621)

<table>
<thead>
<tr>
<th>Number</th>
<th>Cube</th>
<th>1st Diff.</th>
<th>2nd Diff.</th>
<th>3rd Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>7</td>
<td></td>
<td></td>
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<td>3</td>
<td>27</td>
<td>19</td>
<td>12</td>
<td>6</td>
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<tr>
<td>4</td>
<td>64</td>
<td>37</td>
<td>24</td>
<td>6</td>
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<td>5</td>
<td>125</td>
<td>61</td>
<td>24</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>216</td>
<td>127</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

etc., etc., ...
Difference Engine

Idea (1812) and Prototype (1820 – 22)
Royal Astronomical Society
Grants (£17,000), Not Patents
For sailors and scholars –
Tolerances
Terminated project in 1833.
Babbage's Difference Engine
Right: The Difference Engine was a special-purpose calculating machine designed by Charles Babbage (above) to produce tables of mathematical functions using the method of differences. This is illustrated in the accompanying table, which shows the differences which can be built up from a column of squares. The left-hand column shows the numbers from 1 to 15, and the one next to it shows the squares of those numbers. Each number in the columns marked 1st and 2nd difference is formed by subtracting the two nearest numbers in the columns to the left: thus 4 - 1 = 3, 5 - 3 = 2 and so on. Notice that the 2nd difference is constant.

This is a simple table of differences. More complicated functions can have three or many more orders of difference. The last order is always constant. The method is useful therefore for verifying mathematical tables as discrepancies will produce variations in the last order of difference. The Difference Engine illustrated is a simplified model capable of calculating to only two orders of difference. It is

Georg Scheutz (1785 – 1873)
Prototype (1833)
Full scale (Paris Exhibition 1853) - Astronomy
British copy (1859) – Life expectancy tables
Analytical Engine
Analytical Engine

A Steam-powered, programmable machine

Moving Numbers Instead of Yarn...

1830 - 1906
Multiply \((ab + c)d = ?\)

<table>
<thead>
<tr>
<th>Number</th>
<th>Variable</th>
<th>Operation</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Card</td>
<td>Card</td>
<td>Card</td>
<td>Card</td>
</tr>
<tr>
<td>1</td>
<td>Places a on Column 1 of Store</td>
<td>Places b on Column 2 of Store</td>
<td>Places c on Column 3 of Store</td>
</tr>
<tr>
<td>4</td>
<td>Places d on Column 4 of Store</td>
<td>1 Brings a from Store to Mill</td>
<td>2 Brings b from Store to Mill</td>
</tr>
<tr>
<td>1</td>
<td>Directs (a \times b = p)</td>
<td>3 Takes (p) to column 5 of Store</td>
<td>4 Takes (p) into Mill</td>
</tr>
<tr>
<td>5</td>
<td>Brings c into Mill</td>
<td>2 Directs (p + c = q)</td>
<td>6 Takes (q) to Column 6 of Store</td>
</tr>
<tr>
<td>7</td>
<td>Brings d into Mill</td>
<td>8 Brings q into Mill</td>
<td>3 Directs (d \times d = q)</td>
</tr>
<tr>
<td>10</td>
<td>Takes (r) to printer</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Policy

Difference Engine
Technical difficulties?
Asymmetric information
  Government skepticism
  Partial Solution: Trusted intermediaries
Grants vs. patents
  No commercial value
  A Single Customer, a Single Problem
    Judging User Needs
    Ex ante vs. ex post

Analytical Engine
(v - c) < 0 ?
Hermann Hollerith & Punch Cards (Pt. 1)
Hermann Hollerith

The Census Challenge
1880 Census
The Populist Impulse

Consultant to Census Bureau (1879)

MIT Professor (1882)
Started with paper tape, which could not be sorted
Studied Jacquard Looms
Electromechanical solution.
First Patents (1884 – 87)

Raising Capital
- Brother in law
- The Library Bureau

Baltimore Health Dept. (1887)
- War Department, New York, New Jersey health records.

Census
- Prize Competition and 1880 Census
- 1890 Census – Rents Machines at $1000/year + $10 penalty for down time
- 1900 Census – Complaints about “monopoly.”
Forms the Tabulating Company

Sells to New York Central (1893 - 1895)
  Free 6-month trial.
  4m freight bills/year
  Performs addition.

Later:
  Travelers Insurance (1895), French Census,
  Russian Census (1896), US Steel and Marshall Field (1900), most railways (1902).
Proliferation of devices (1893 - 1914)
Accumulator, keypunch, card sorters, adding punch, printer.
Policy

Selling to Both Public and Private Sectors
Makes “v” large enough to cover “c”?
Who gets the benefit of civilian sales?

Asymmetric Information
New York Railway Offer
Renting machines
Internal Financing & Market Implications

Types of Innovation
New Technology vs. Finding & Meeting User Needs
1900 - 1940
New Needs (Pt. 1)

Progressive Governments

Big Business
Factories, steel mills, insurance companies, electric light, traction, phone, wholesale companies, textile mills, automobile companies, railroads, municipalities, state governments.
Pre-WWI: Labor costs, efficiency records, sales distribution, internal requisitions for supplies and materials, production statistics, day and piece work, fire, life and casualty risk, plant expenditures and sales of service, public service corporations, distributing sales and cost figures to salesmen; special reports.

“Batch Processing.”
A consequence of (v-c)?
Hollerith $Ctd\ldots$
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1900</td>
<td>Census</td>
</tr>
<tr>
<td>1901</td>
<td>McKinley Assassination, David Porter fired.</td>
</tr>
<tr>
<td>1905</td>
<td>Congress establishes $40,000 R&amp;D Unit</td>
</tr>
</tbody>
</table>
| 1906 | Census Demands lower prices  
Employees keep patents, government receives free license. |
| 1910 | Census does not use Hollerith machines. |

Hollerith Sell Out; Merger forms Computing Tabulating Recording Company (CTR).
Was Congress Right?
Who benefits from commercial sales?
*Ex post vs. ex ante* efficiency.

Schumpeterian Competition
Joseph Schumpeter (1883 – 1950)
Innovation vs. Monopoly
- Monopoly funds innovation
- Monopoly is temporary
- Technological revolutions.
- Long-run efficiency.
Analog Computers
Warfare

Example 1: Firing Tables

Gravity, ground hardness, atmospheric density, Coriolis effect, density changes with altitude.

Fifteen multiplications, square root calculated at 0.1 to 0.01 second intervals. Check function every four calculations. Five days by hand.

2-4000 trajectories per firing table

Example 2: Atomic & Hydrogen Bombs
Big Science
(Mostly astronomy)
James Clerk Maxwell (1831 – 1879)
Sir William Thomson, Lord Kelvin (1824 – 1907)

2d order equations
Tide tables.
The Torque problem
Vannever Bush
(1890 – 1974)
1920s Machine
Adding voltages,
Electric meters as integrators

1930s Maxwell Machines
Servomotors + Torque
Amplifier
1930 Differential Analyzer
100 tons, eighteen integrators
2000 vacuum tubes, 150 motors, 200 miles of wiring.
1935 Differential Analyzer
$85,000 Rockefeller grant.
Electrical components
Paper tape instructions

Cyclotron Culture: Copies at Moore School, Aberdeen, Cambridge & Leningrad.
Policy

Grant Funding
Cyclotron culture
No civilian applications…
The Rise of IBM®
1914: Thomas J. Watson becomes CEO

National Cash Register Experience

Central advertising, tech support, credit, and in-house R&D.

Antitrust

1921: Patent Wars

Remington-Rand’s crisis

Joint Monopoly Pricing

Litigation and Purchases

1924: CTR Becomes IBM

1928: Separate standards

Customer Lock-in.

Thomas J. Watson, Sr. (1874 - 1956)
R&D Competition

Competition with Powers spurs R&D.
Parallel, competing R&D teams

New Technologies
Subtracting tabulator (1928)
Type 600 multiplying punch (1931)
Type 285 Numeric Printing Tabulator (1933)
Type 405 Alphabetic Printing Tabulator (1934).
R&D Competition

A Complex and Capable Technology
Type 405 Electric Accounting Machine (1930)
55,000 moving parts
75 miles of wiring
Dominant data processing device until 1962.
1500/year manufactured through late 1960s.
New Technologies ctd. …

From Mechanical to Electromechanical to Electronic

F = Ma
Magnetic card, tape & drum research (1930s)
Replacing Wheels with vacuum tubes.
Electronic adder (1940)
Electronic multiplier circuit (1941)
And New Uses…

An IBM Specialty.
Methods Research Department (1930s).

Big Government:
415 machines/120,000 square foot building.
Also: Employer reporting, public works projects.
IBM sales grow from $26m in 1936 to $45m in 1940.
Antitrust Issues

Innovation isn’t everything

*Ex ante* vs. *ex post* efficiency

Multiple Tipping Dynamics

Internal financing
Reputation
Complex products in a small market
Patents
Business cycle shocks
Standards and customer lock-in.
Returns to R&D
Antitrust Issues
Returns to R&D

Price

Quantity

Profit

Cost
Antitrust Issues

Returns to R&D

\[
\text{Reward} = L \times W
\]
Antitrust Issues

Cards and Leasing

Leasing

Internal financing/information asymmetry?
Barrier to entry?

Three bn. cards/year.
Price discrimination

Cards and The Depression.
Cards as Standards

1936 Consent Decree

85% Share by late 1930s.
Using Tabulators to do complex scientific calculations.

- Machine-graded Tests (1928)
- Difference Methods (1929)
- Thomas J. Watson Astronomical Computing Bureau (Columbia U.)
- Calculation Control Switch (1936)
- Cam-driven sequence of arithmetical operations
Academic Interactions

Howard Aiken (1900 – 1973)
A trip to Harvard’s Attic
An electromechanical machine for calculating trigonometric functions and exponentials.
$100,000 estimate (1939)
$400,000 price tag (1943).
Academic Interactions

Harvard Mark I Computer
“Babbage’s Dream Come True”
But: No “if” branch.
Paper tape + 1,728 counter wheels
But: vacuum tubes for storage.
Wheels machined to 1/100,000 inch.
5 tons, 51 feet long, 530 miles of wiring.
“Like the roar of a textile mill…”
Schumpeterian Competition
An Unstable World?

Academic Exploration
Extracting benefits from IBM’s monopoly?
Lead users?
Looking at v:
Governance, Military, Science, Commerce.
Computers focused on military problems.
Grant funding for Military & Science
Schumpeterian dynamics for Governance and Commerce

Looking at c:
Beginning to use vacuum tubes and relays.
*Modest* cost savings.
*Marginal* cost is high.
A few large machines.
Coming Attractions

V:
Technology: True computers, new capabilities.
New Uses: Finding a civilian market.

C:
Falling Costs: Vacuum tubes, software, integrated circuits.

Schumpeterian competition continues…
Wartime
Overview

Vannevar Bush and OSRD
World War I Experience
Organizing Work the Big Science Way

Ultra, Bletchley Park & All That
Colossus (1500 vacuum tubes)

Stibbitz and ENIAC
George R. Stibitz

Bell Labs (1937)
   Telephone Relays
   Binary Arithmetic

K-Model (1938)

Model 1 (1939) - $20,000

Models 2-5 (1940 - 45)
   Paper tape, error checking,
   multiplication tables, &
   storage registers.

NACA and Aberdeen
Electronic Logic

Vacuum Tube (Or Relays or Transistors)

Glass envelope
Plate (anode)
Grid
Filament (cathode)

S = AxorB
C = AandB

Half-Adder

S = AxorB
C = AandB

Flip-Flop

Binary Arithmetic

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>S</th>
</tr>
</thead>
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<td>0</td>
</tr>
</tbody>
</table>
Atanasoff-Berry

“ABC Computer”
Iowa State (1937 – 39)
Arithmetic – Base 2 Logic
Memory – Drum, Condensers + “Jogging”
Output – Cards
No “if” statement.

Proposed 300 vacuum tube machine was never completed.
Konrad Zuse

Z1  Binary Addition (1936).
    Mechanical, punched tape.
Z2  Relays (1940).
Z3  Programmable (1941).
    2600 relays.
Z4  Refined Z3 (1945)
    2000 vacuum tubes.
1939: Fuses instead of vacuum tubes.

1941: An electronic Differential Analyzer
- $486,804.22
- 200,000 man hours

174kw, 17468 vacuum tubes, 500,000 soldered joints, 70,000 resistors, 10,000 capacitors.

Completed in the Fall of 1945, used on “The Super.”
Math Units
  20 accumulators
  Flip flop “wheels” + Tables

Memory

Program
  Plug board, cables, switches.
Looking Ahead

The Software Concept
The magnetic drum/disk idea (1944)
John von Neumann (1903 – 1957)
First Draft of a Report on the EDVAC (1945)
Policy

The Wartime Research Miracle
OSRD, National Labs
Money
The Research Backlog + Focused Projects
Industry/Academic Cooperation
Big Science Research Model
… and Wartime Ethics?
Policy

A Role For Patents?

Eckert and Mauchly leave The Moore School.

An essential incentive?
Commercial vs. academic machines.

S. Reid Warren (Moore School): “[The School’s patent policy] was very, very naïve. We didn’t go out of our way to help people, and our general attitude was, ‘Let’s make it so it’s helpful to the human race and so on.’”
The World at 1945

(v-c)

Looking at v:
Governance, Military, Science, Commerce.
Computers focused on military problems.

Looking at c:
Electronics: Vacuum tubes and relays.
*Modest* cost savings.
*Marginal* cost is high.
A few large machines.

Winner take all dynamics
Schumpeterian Competition?
Coming Attractions

Looking at v:
Technology: True computers, new capabilities.
New Uses: Finding a civilian market.

Looking at c:
Falling Costs: Integrated circuits and software.

Schumpeterian competition continues…

Policy Levers
  Military spending.
  Antitrust (again).