What Will Carry the Industry Beyond the Tradition of Moore's Law?

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Value Growth in Semiconductors is created through **FIVE** mechanisms:

• Moore’s Law: Economic Performance
• Dennard’s Law: Device Performance
• Koomey’s Law: System Performance
• Metcalfe’s Law: More Users
• Emergent Behavior: Innovation
Moore’s Law

Component density doubles every two years due to geometry shrinks for roughly the same areal cost.

Gordon Moore - 1975

Gordon Moore in 1975 Source: Intel
Moore’s Law Drives Semiconductor Growth

- Price-per-Transistor trend is critical for Electronics and Semiconductor demand
- Ability to integrate more and more functionality at lower cost into a chip is the core of the demand function
- It’s about More for Less
  - More Value
  - Less Cost

The Transistor Pricing History of Moore’s Law

- First Commercial IC’s sold (1963)
- Moore’s 1st paper Density Doubles every Year (Electronics ‘65)
- Moore’s Law Rate of Decline
- Average Price Per Transistor
- Integrated Circuit Invented (1958)
- Moore’s “No Exponential is Forever” paper (VMIC ‘93)
- Moore’s “But, Forever can be Delayed” paper (ISSCC ‘03)
- Moore’s 2nd paper Doubles every 2 Years (IEDM ‘75)
- 1 year to halve Ppt
- 3 years to halve Ppt
- 1.5 years to halve Ppt
- 2 year rate
Koomey’s Law

- Computer power efficiency grows at a 54% CAGR
- Thus power-per-computation is declining at a 35% annual rate
- Due to gains in:
  - System Architecture
  - Moore’s + Dennard’s Laws
  - Lithography Scaling
  - Materials Scaling
Dennard’s Law

Transistor **shrinks** result in **proportional power** and/or performance **gains**

*Robert Dennard – 1974*

**Dennard’s Law in spirit:**
Performance gains-per-node have come from **Materials-Enabled Scaling** since <100nm

Robert Dennard Source: IBM
Metcalfe’s Law

The value of a network is proportional to the square of the number of connected users of the system.

Robert Metcalfe - 1993
Emergent Behavior

The Semiconductor Innovation Model:
It’s far more than technology and collaboration
Our Innovation Model:
It’s far more than technology

Chip innovation comes from
massively scaled collaboration
that is globally interconnected
How Semiconductor Innovation is Different

Hundreds of companies with thousands of people solving millions of problems still hitting each node on together linked in time in a Virtuous Cycle
Why it all gets bundled into “Moore’s Law”

All the other technology laws are not possible without **Moore’s Law**

- **Koomey’s Law** needs more transistors to improve architectures
- **Dennard’s Law** needs to get devices closer together
- **Metcalfe’s Law** needs lower prices to attract more users
- **Emergent Behavior** needs a simple rule to create order from chaos
Moore’s Law Extended through Bundling

• The bundling effect in search result numbers:
  – Moore’s Law  1,930,000
  – Metcalfe’s Law  67,900
  – Dennard scaling  31,100
  – Koomey’s Law  27,000

• Who’s going to say the future is here because of Moore’s, Metcalfe’s, Dennard’s and Koomey’s Laws?

• Thus ‘Moore’s Law’ is more than scaling
Is Moore’s only about density and lower cost?

- No
  - Lower Cost and More Transistors are not enough
  - Moore saw this in 1965:
    - More performance
    - Less power density
What about Moore’s 2nd Law?

• Moore never said it
• Siemens noted it as Hutcheson’s law in 1990
• Intel noted it as Rock’s Law

• Chart proves you can
  – ‘forecast long’
  – Trend still fairly accurate
Did Fab Cost Matter?

- No
  - Moore’s Law enabled
    - More Cost
  - OK as long as price-per-transistor goes down
More Moore vs. More than Moore?

- Simply replace ‘Moore’ with ‘Transistor’

- More Moore =
  - More Transistors

- More than Moore =
  - More than Transistors
  - Everything else falls into this bucket
    - MEMS
    - Heterogeneous
    - Etc.
Many Moore’s Law Variants

For **insiders** it’s

• A doubling of density every 2 yrs.
• A performance doubling cadence
• Tied to the PC
• Tied to MPUs
• Something too expensive
• Not relevant to AI or Mobile
• Something of Intel’s that …
  – Should be denigrated by competitors
  – Because yours is better …

To the **outside** world it’s

• A magical thing that has brought magical products into our lives
  – a la Steve Jobs
• Innovation that can be taken to the bank
  – Governments fund it
  – Financial Institutions bet on it
The Problem with Denigrating Moore’s Law

• We hurt ourselves because
  – We can’t define anything to replace it
    That has the same power
• We imply that our innovation engine is
  – Slowing or
  – Stopped
• If so, why do so many continue to invest in packing more transistors into a square mm
  – Even ones who say it’s dead
  – Ans. The need for more compute power never abates
Moore’s Law Clock has slowed

- From 1.5 years in the NTRS era
- To 2 years this decade
- The greatest gains are in memory
  - Especially as NAND went vertical
- Systematically profitable
- ML has …
  - great brand value
How important is the 2 year clock?

• The data shows exact timing is a mythology
  – Only a few companies meet it

• What’s important is continued
  – Density growth
  – 3PC
    • Price, Performance, Power, and Connectivity

• Without innovation
  – Nothing moves forward
Shifting out of Moore’s Law and into The Law of Value

- **3PC** — Price, Performance, Power, and Connectivity
  - Value growth from transferring data faster using less power each year
- Chip Price/Performance rising
  - Cost/Performance Declining
- Profits soaring
  - Silicon is sexy again
What’s Moore’s Law? … Really?

Why do we need a clock?
• Aligns individual actors towards a common goal

Carver Mead coined the term
• He saw it as a way to spur innovation … in other words it’s …
• Emergent Behavior leading to
  – A Virtuous Cycle

This is a law [of] the way that humans are. In order for anything to evolve like our semiconductor technology has evolved, it takes an enormous amount of creative effort by a large number of smart people. They have to believe that effort is going to result in a successful thing or they won’t put the effort in. That belief that it’s possible to do this thing is what causes the thing to happen.

The Moore’s Law thing is really about people’s belief in the future and their willingness to put energy into causing that thing to come about. It’s a marvelous statement about humanity.

– Carver Mead speaking to Rachel Courtland
  15 Apr 2015, spectrum.ieee.org
Virtuous Cycle:

A complex chain of events that reinforces itself
The 4 Laws that Create Virtuous Chip Cycles
— Each inspire action via our innovation model

Moore’s Law
Bigger & More Markets
- More Transistors
- Better Tools & Materials
- More Performance

Dennard’s & Koomey’s Law
Bigger & More Markets
- New Apps & Devices
- More Compute-per-Watt
- Better Architectures

Metcalfe’s Law
Bigger & More Markets
- More Network Nodes
- More Users
- Network Value = n²

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5 Virtuous Cycles of Demand

Integration Scale in Transistors

Tens  Hundreds  Thousands

IC  Transistor  Radio  Mainframe

Moore’s Law  Cell Phone  PC  Video Game

AT&T Broken Up


Billions  Millions  Trillions?
5 Virtuous Cycles of Demand

Integration Scale in Transistors

Tens  Hundreds  Thousands

IC  Moore’s Law  DRAM  Laptop

Radio  Cell Phone  Video Game

Military  PC  Internet

Broadband  MPU  High Speed Modem

Digital Cellular

AT&T Broken Up


Billions  Trillions?

IoT  Cloud  Social Media  Search  Smartphone  Touch Screen

Cellular  Block Chain  Cognitive AI

Neuromorphic IC  Multicore APU & NAND

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5 Virtuous Cycles of Demand

Integration Scale in Transistors

- Tens
- Hundreds
- Thousands

IC

- Transistor
- Radio
- Mainframe

Moore's Law

- Cell Phone
- Military

Drum

- MPD
- Game
- PC

High Speed Modem

- Internet
- Digital Cellular

Multicore

- APU
- NAND

Neuromorphic IC

- Cognitive
- AI

Blockchain

- IoT
- Cloud

- Social Media

- Search

Touch Screen

Billions

- Trillions?

- AT&T Broken Up

The Strategic Nature of Cognitive Computing

Cognitive Computing is the Future of Computing

What’s Smart will become Cognitive

It will draw the world into it like Precision Computing did in the 50 years before it
Why IoT will drive the Cloud

- **Smart Phone User Today**: 0.03 average GB-per-Day of Data Used
- **Person by 2020**: 1.5
  - **Autonomous Vehicle**: 4,000
  - **Airplane Jet Engine**: 40,000
  - **Smart Factory**: 1,000,000

Source: Brian Krzanich & Jeff Imelt, @ IDF 2016, Verizon
Why IoT will drive 5G Wireless Networks

Billions of Wireless Connections Worldwide by 2021

- Mobile Phone Connections: 12
- IoT Mobile Connections: 16
- Total Wireless Connections: 28

Source: Ericsson
Data Rivers and Streams of the Cloud and IoT

Data is the Currency of the Future

IoT Verticals of objects around the Edge

VLSI research ... intelligence to make better decisions faster
The Zetta-Data Era

• 1.5 Zeta-Bytes in 2017
  – >1E+21 Wired
  – >9E+19 Mobile

• Based on Trend:
  – 9.5 Zeta-Bytes in 2025
    • >6E+21 Wired
      – 21% CAGR
    • >3E+21 Mobile
      – 46% CAGR

• Trend is pessimistic
  – It’s not maturing
Data Rivers and Streams of the Cloud and IoT

Clouds of Cognitive Clouds

IoT Verticals of objects around the Edge
The Zetta-Data Era: The Road to 2025

- Autonomous Vehicles
  - 1 AV = 4 TB
  - By 2025 – 8 ZB
    - 20% penetration
- Smart Home
  - 1 HD camera = 36 MB
  - 1 Home = > 2 TB
- Smart Factory
  - 1 Smart Factory = 1 PB
- Smart City
  - >200 Data Stream Classes
- To sum it up =
  - 1.75E+22 Bytes of Data transmitted-per-year

2025 Internet Data Traffic: New Drivers

- 110M AVs
- 500M Smart Homes
- Other IoT/AI
- 1K Smart Factories

Forecast

Bytes-per-Year

2005 2010 2015 2020 2025

Internet Data Traffic History_170924d

Source: Cisco, VLSI

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Data Rivers and Streams of the Cloud and IoT

Everything runs on Silicon
Data drives silicon consumption

- PC & the wired internet drove demand
  - It matured
- Smart Phones & the wireless internet drove demand
  - It’s maturing
- Next up:
  - More Smart
  - Cognitive Era of AI
The Next Wave: Cognitive AI + IoT edge devices

- **Smart =**
  - Call and Response
    - i.e. Alexa... set alarm for 10:00 PM
  - Links multiple databases
    - i.e. Calendar, Contacts, Maps, Music, etc.

- **Cognitive =**
  - Learns and understands
    - i.e. Wake me if my daughter comes in after curfew
  - Builds databases
    - Knows what you want
The Cloud has made IT a profit center

- Amazon, Apple, Facebook, Netflix and Google, or FANG:
  - A revolution in value creation

- Captive Fabless Semiconductor Production to reach $14B* in 2017

* Merchant Market equivalent revenues

Relative Production Rank:
1. Apple
2. Cisco
3. Huawei
4. IBM
5. Oracle
6. Google
7. Facebook
8. Tesla
Shifting out of Moore’s Law and into **The Law of Value**

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Beyond Moore’s Law:

• The Cloud has made IT a profit center
  – Amazon, Apple, Facebook, Netflix and Google, or FANG: a revolution in value creation

• “Software comes and goes. Hardware is forever.”
  — *Halt and Catch Fire*, S1E3
  – Software maxed out
  – Data center optimized
  – Now they’re turning to Silicon

• The Law of Value:
  – **3PC** — Price, Performance, Power, and Connectivity
  – Value growth from transferring data faster using less power each year

• Chip Price/Performance rising
  – Cost/Performance/Declining

• Profits soaring
  – **Silicon is sexy again**
Why NAND Demand Seems Limitless

- Data must be stored
- Storage = Memory

- More Data = More Memory

- *Consumable versus durable good changes market dynamic*

**New World:**

Data Centric

**Old World:**

Computation Centric
The future of integration ...

- It’s heterogeneous
- Horizontals across IP and CHIP platforms will matter most
- Competitive advantage will come from platforms that access to best sensors and memory . . .
- Memory that has high bandwidth and low power drain
But integration must branch out in different directions...

- For differentiation
- To control cost
  - Planar is only effective when added structures don’t add process complexity
- Competitiveness will hinge on having the best heterogeneous platform
Why heterogeneous?

- Die sizes constrain density
- Trade-off chip yield for package yield
- Limit mask counts
- System performance gains can’t be made on boards
  - Chips must be closer
FORECASTING LONG

Just remember, whatever has been done, can be outdone!

Gordon Moore

This is Moore’s wisdom on Moore’s Law and life in general; whatever you’ve done, will be outdone. It’s your decision: Will it be someone else or will it be you doing the outdoing. The paired photo speaks to the wisdom that after each sunset, there will be a sunrise. It’s up to you to make the most of each day. Kona Sunset, Hawaii. Why it Works: Nothing’s more relaxing than a sunset. But the boat with the breaking wave makes it different. Plus, the two draw a diagonal that intersects the falling diagonal of the clouds, drawing the eye to the Ro3 point where the sun and the boat are.

Reference number: HL_14_312
2050 in perspective: IC Manufacturing

- 2000 nm
- 100K transistors
- Fabs cost $26M
- Moore’s Law stalled
- 1 Micron Barrier

- 60/14 nm
- 2G transistors
- Fabs cost $10B
- Moore’s Law slowing
- Multi-P/EUV Barrier

- 1.8/0.1 nm?*
- 40P transistors*
- Fabs cost $3.4 Trillion?*
- Is Moore’s Law over?

* Compound Extrapolation
What they got wrong in 1980

• Optical lithography was not dead
  – Steppers were the dark horse
• Fab cost and tool prices not the issue
• Automation was not about “Lights-out” fabs
  – It was about **DESIGN** Automation
• Moore’s Law was for more than memories
• Silicon was not replaced by GaAs
• Home computers were not toys for geeks
• Computers and communications were not separate industries and apps
How much of today was forecasted \( -30+ \) years ago

“We want to put an incredibly great computer in a book that you can carry around with you …”

— Steve Jobs, "The Future Isn't What It Used To Be," 1983
How much of today was forecasted t-30+ years ago

"And we really want to do it with a radio link in it so you don't have to hook up to anything and you're in communication with all of these larger databases and other computers."

— Steve Jobs, "The Future Isn't What It Used To Be," 1983
How much of 2015 was forecasted to be 30+ years ago?

HP vision piece about an executive who, on landing, turns on his handheld administrator and it wirelessly updates him on what’s changed while he’s been enroute.

— Earliest prediction of a smartphone
How not to get it wrong for 2050

• **It’s not** about technology
  – "Nuclear-powered vacuum cleaners within ten years."

• **It’s about** drivers, needs, benefits, and using innovation to deliver value
  – That’s how Steve Jobs and others did it
  – Lesson: Never lose sight of the long-term

*The future is waiting to be invented*
2050 in perspective: Business Model Drivers

1980 -35 Years

- Big Box Computers
  - PCs & cell phones emergent
- Business
  - Consumer was the flop of 70’s

2015 Year 0

- PCs and Smartphones
  - IoT & Big Data Emergent
- Consumer

2050 +35 Years

- IoT & Big Data ?
  - What’s Emergent ???
- Consumer & Business
- Shift from one-time sale
  - To subscription models?
React Fast or become somebody else’s Lunch

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