

Visualizing a Classic CPU In Action: The 6502

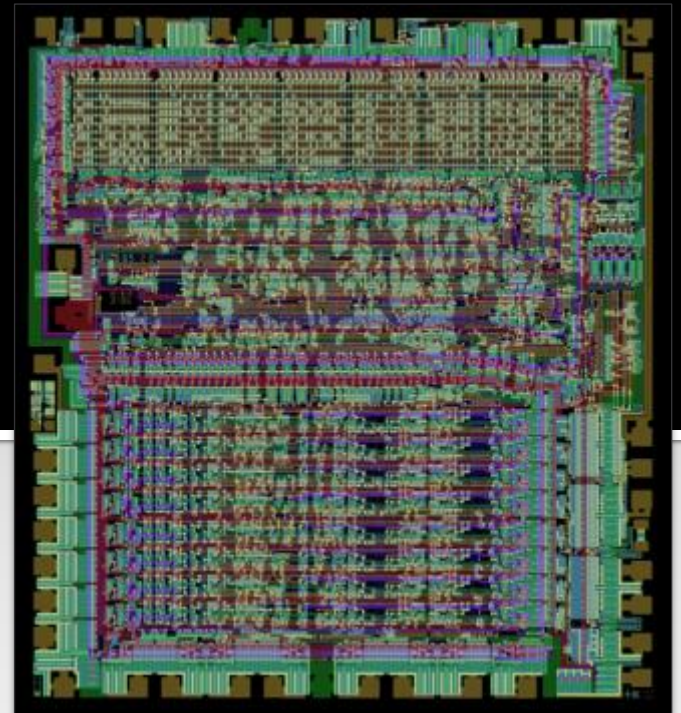
SIGGRAPH 2010

July 27th, 2:00 pm, Theater 411

Greg James

Barry Silverman

Brian Silverman



Web distribution note, August 1, 2010



This project is an ongoing collaboration between Greg James, Barry Silverman, and Brian Silverman, began in the summer of 2009. We seek to preserve, document, and understand historic computer systems, and to present them in a highly visual manner for education and inspiration.

We're always looking for classic computer hardware in danger of being lost, especially broken or non-functional components created before about 1986. Before recycling or tossing your old computers or game systems, please check our website to see if they could become a valuable contribution to computer history.

www.visual6502.org

A presentation similar to this was given at SIGGRAPH 2010, July 27th 2:00 pm in the "Visualization for Art and Design" track chaired by Esther Lim. The theme for this SIGGRAPH was "The People Behind the Pixels," and this work is very much in honor of the architects and visionaries who enabled our first pixels.

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Introduction



MOS Technology's 6502 CPU

Released 1975

Apple I, II

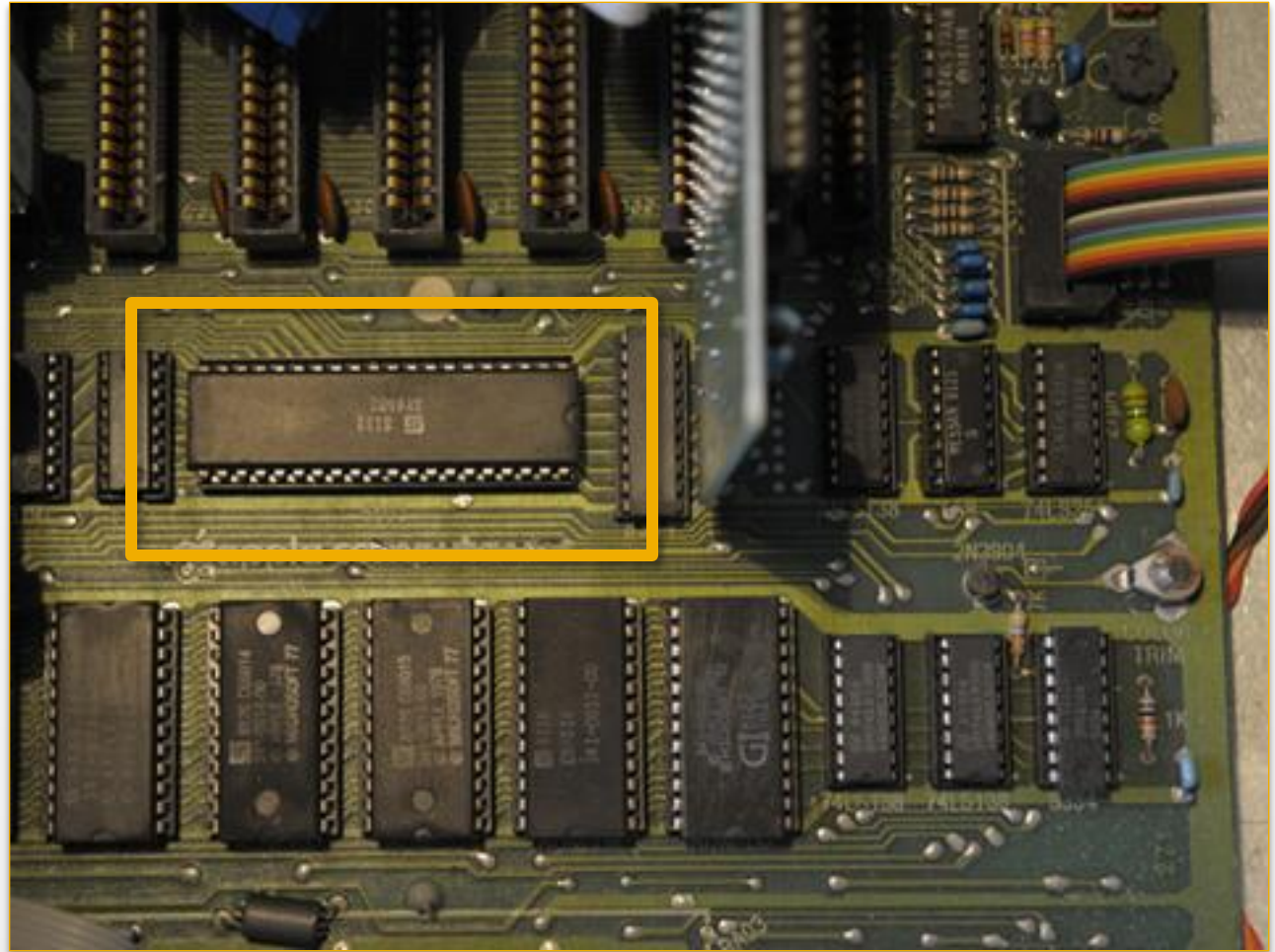
Commodore PET, C64

Atari 2600 (6507)

Atari 400, 800

Nintendo NES

Apple II Plus motherboard

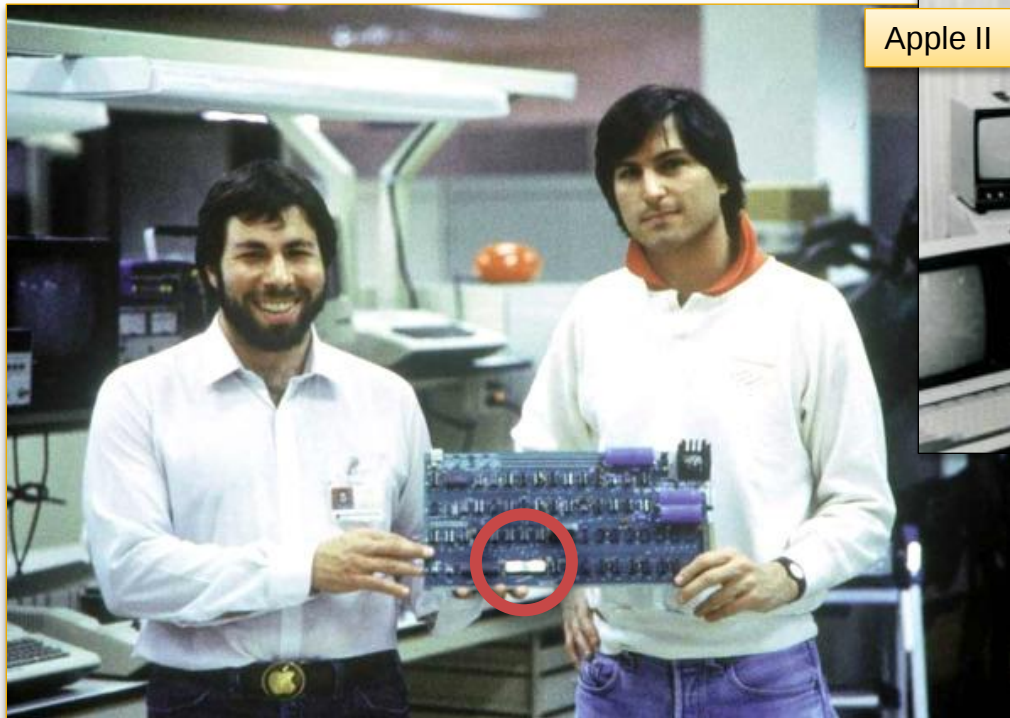


6502 – Everywhere



Paul Allen, Bill Gates

Steve Wozniak, Steve Jobs



Apple I

[Klein] CCL 1.3

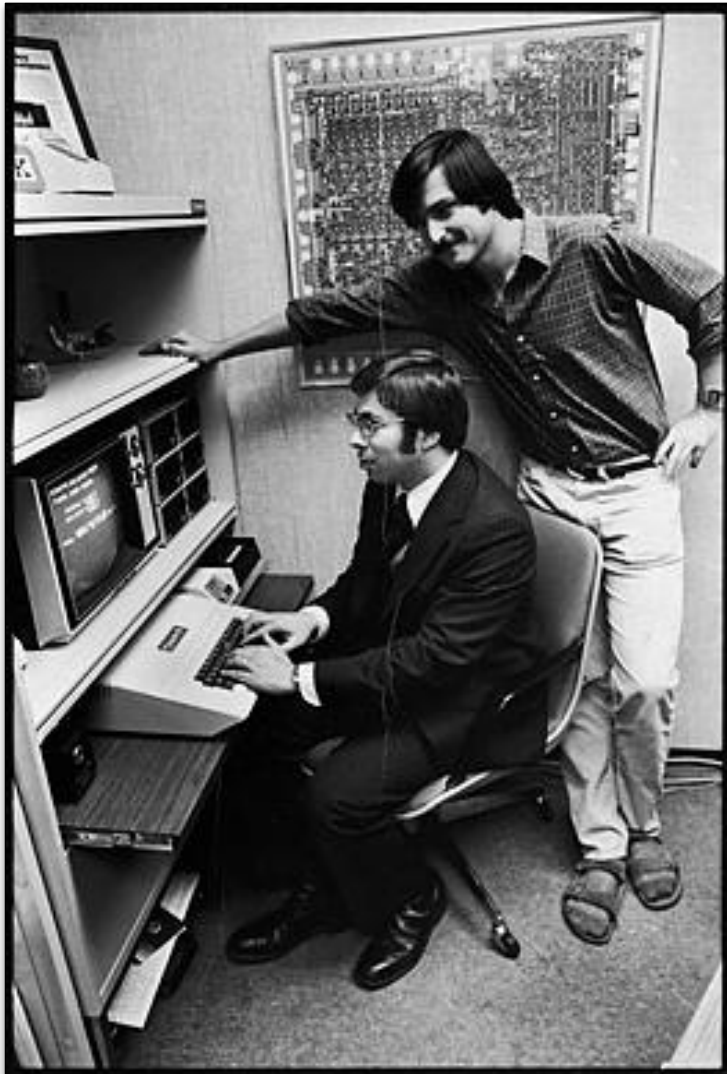


Apple II

[Klein] CCL 1.3

Commodore PET

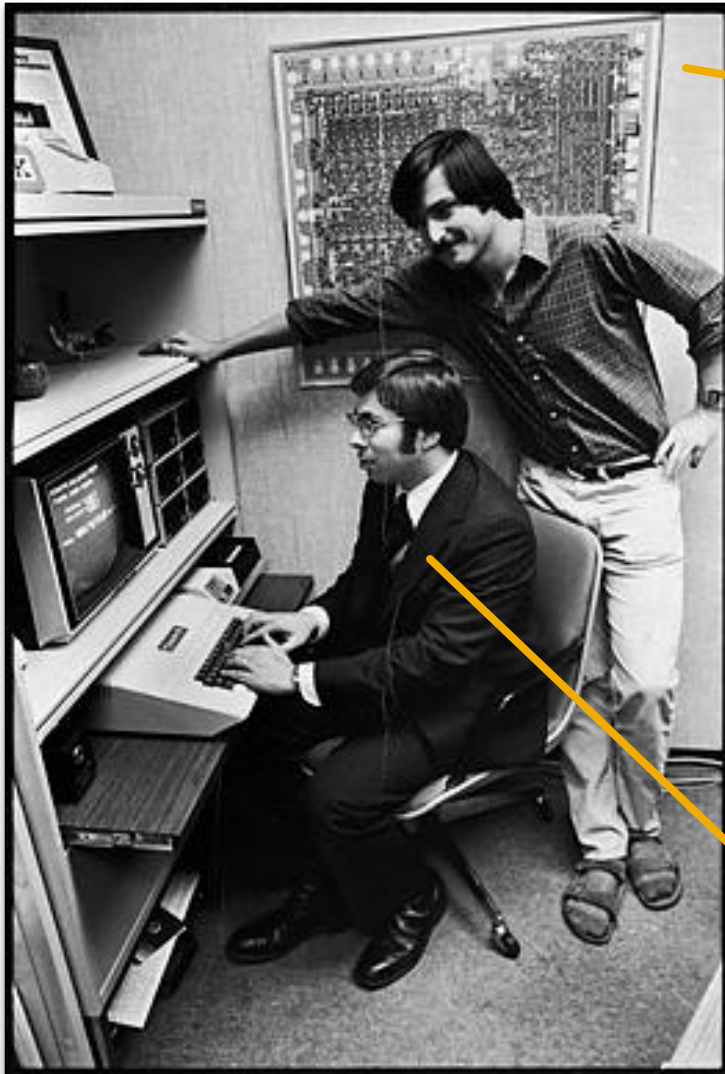
Wall Art?



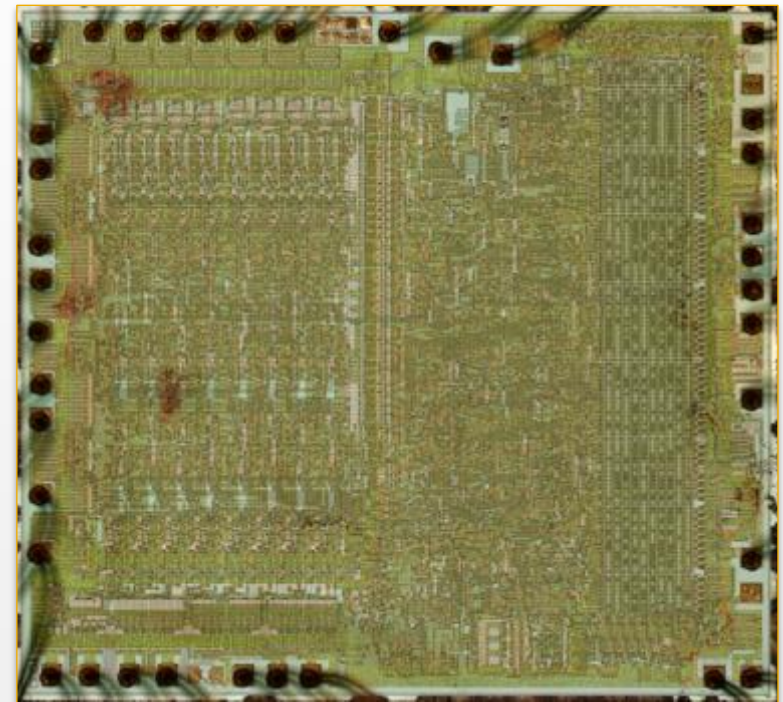
Jobs, Wozniak, and ...

[Klein] CCL 1.3

Wall Art: 6502 die shot



Jobs, Wozniak, and ...



The 6502

Motivation

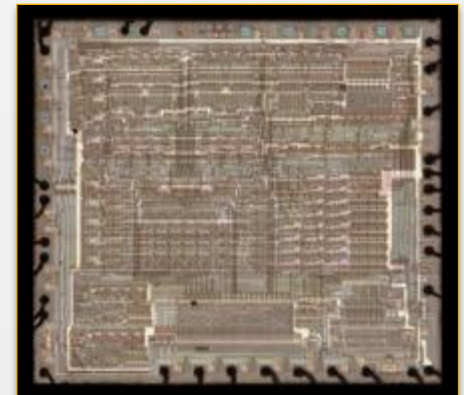


- Who's seen a transistor?
 - or a network of them doing work?
- Understand a CPU by seeing it operate
- Preservation
 - Simulation, not emulation
 - 100% accurate model
- Honor the people behind my first pixels
 - Their design achievements, hidden work.

Introduction



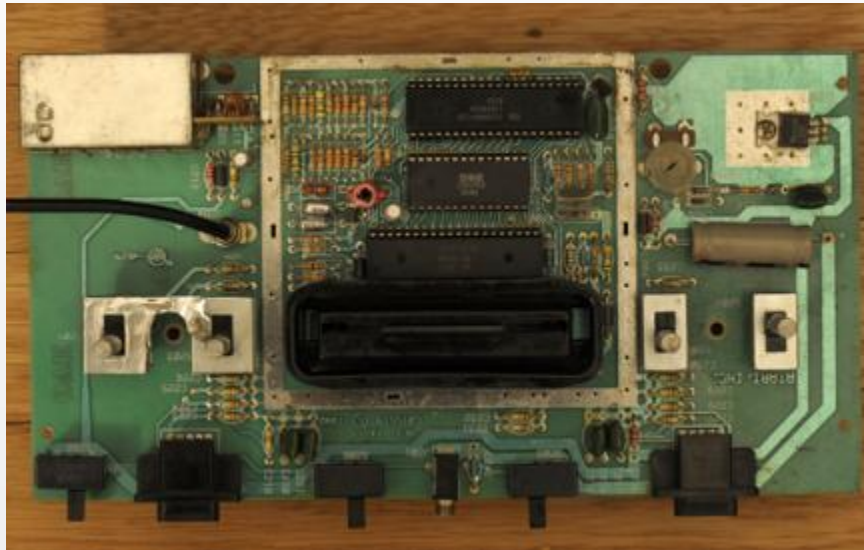
- Began August 2009. Ongoing
- The Journey
 - 1 Chip → Bitmaps → Polygons → CPU sim
 - 100% accurate working 6502 chip
- Visual tour as the chip computes
- A little surprise
 - More than just the 6502



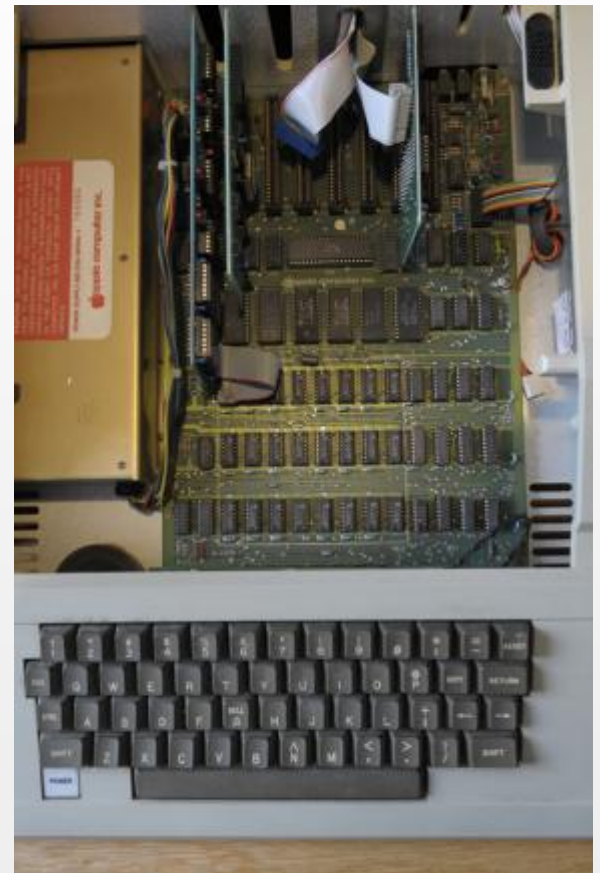
My First Pixels. Two 6502s



- 1981. I was eight
 - Atari 2600 game system



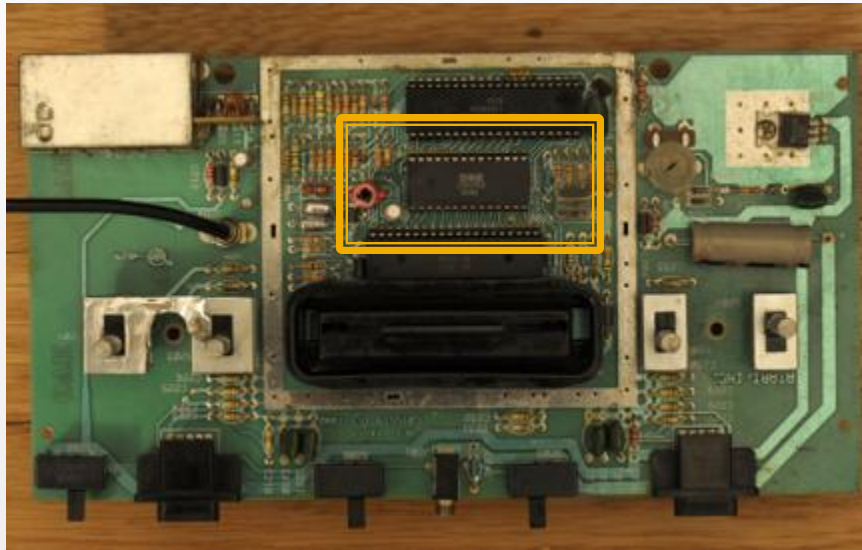
- Apple II+



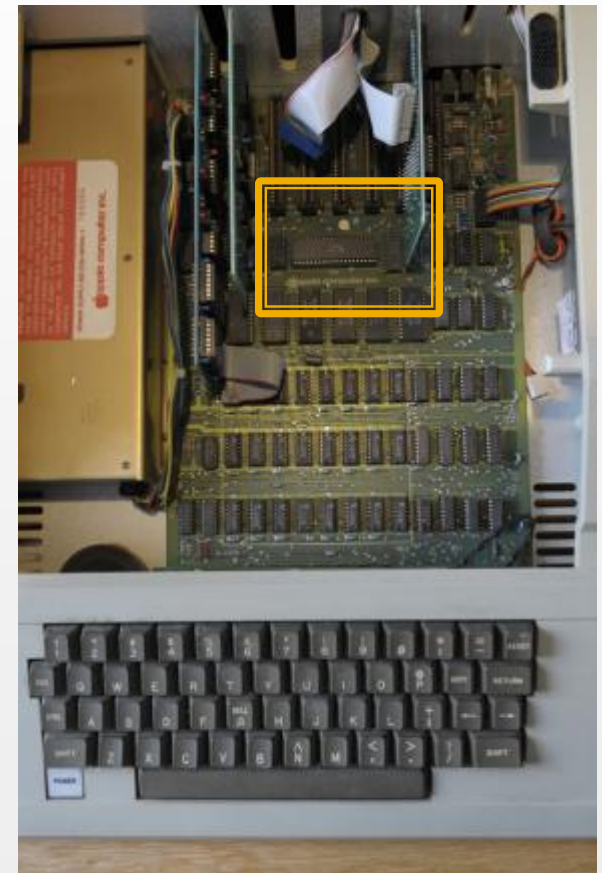
My First Pixels. Two 6502s



- 1981. I was eight
 - Atari 2600 game system



- Apple II+



-

CPU Transistor Counts 1971-2008 & Moore's Law

Transistor count

Curve shows 'Moore's Law': transistor count doubling every two years

Date of introduction

Processor	Approx. Date of Introduction	Approximate Transistor Count
4004	1971	2,300
8008	1972	6,000
8080	1976	29,000
8085	1982	290,000
286	1985	275,000
386	1989	1,200,000
Pentium	1993	3,100,000
P5	1995	5,500,000
P55C	1996	5,500,000
P55C	1997	5,500,000
P55C	1998	5,500,000
P55C	1999	5,500,000
P55C	2000	5,500,000
P55C	2001	5,500,000
P55C	2002	5,500,000
P55C	2003	5,500,000
P55C	2004	5,500,000
P55C	2005	5,500,000
P55C	2006	5,500,000
P55C	2007	5,500,000
P55C	2008	5,500,000

Wikimedia Commons, [GFDL](#)

Chip Design by Hand, c.1976



- No digital representation

- Designs lost

- No computer optimization

- Interesting physical features

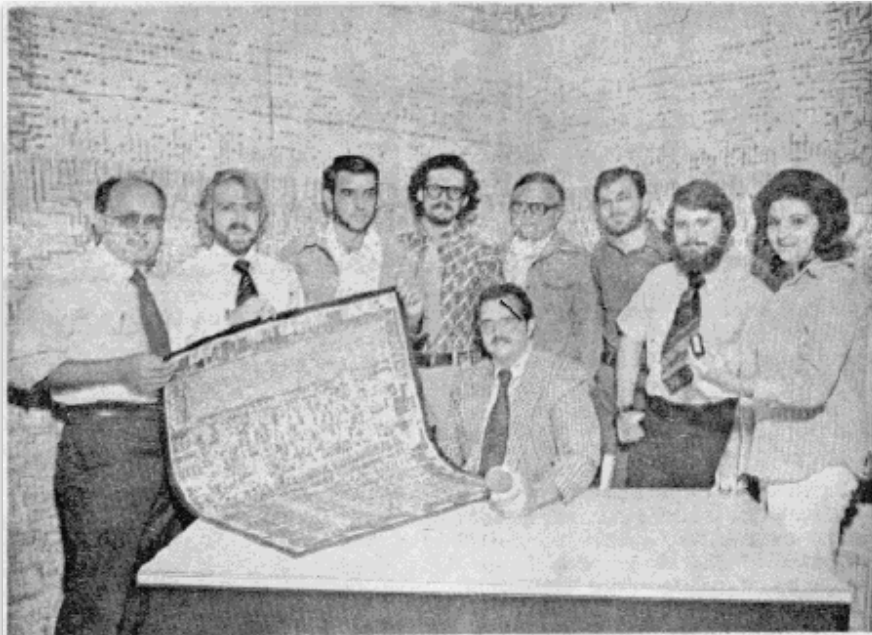


[Volk'01] Used with permission

MOS 6502 – Fascinating!



- 3510 transistors
- Designed by hand
- “undocumented” instructions – mystery!
- ~1/5 the price of its competition in 1975



MOS designers with Rubylith 6502

L to R:

Layout Designers:

Sydney-Anne Holt, Michael Jaynes,
Harry Bawcom.

Design Engineers:

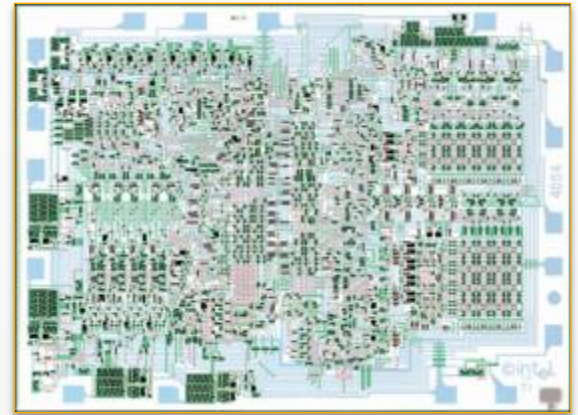
Chuck Peedle, Ray Hirt, Rodney
Orgill, William Mensch, Wilbur Mathys.

Seated, Product Manager: Terry Holdt

Prior Work

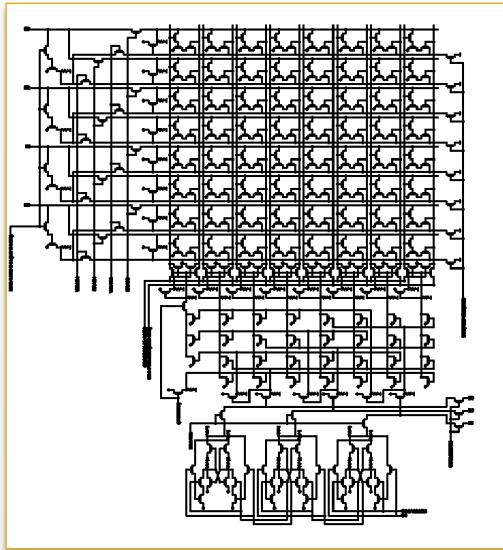


- Intel 4004 35th Anniversary Project
 - <http://www.4004.com>
- Intel released the masks
 - Masks make the chip
 - [Photolithography](#)
 - People transcribed the masks
 - Made schematics
 - Error prone
 - Relation of schematic to chip die is not obvious
 - Animated schematic, Fall 2009

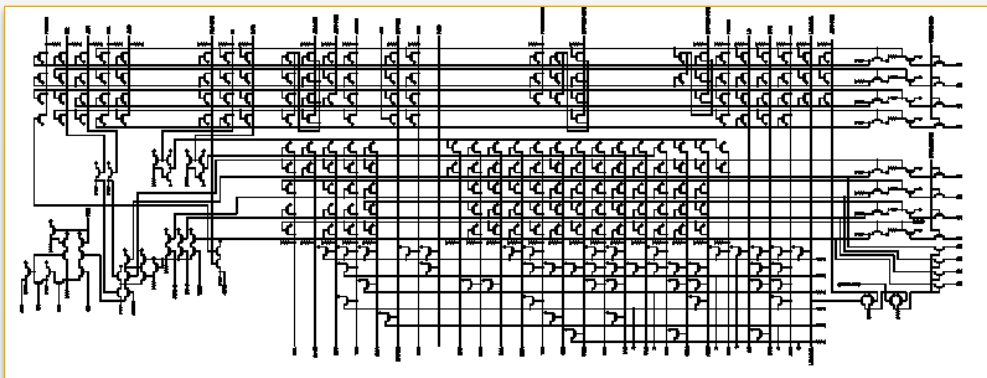


Intel 4004 Project, CCL1.3

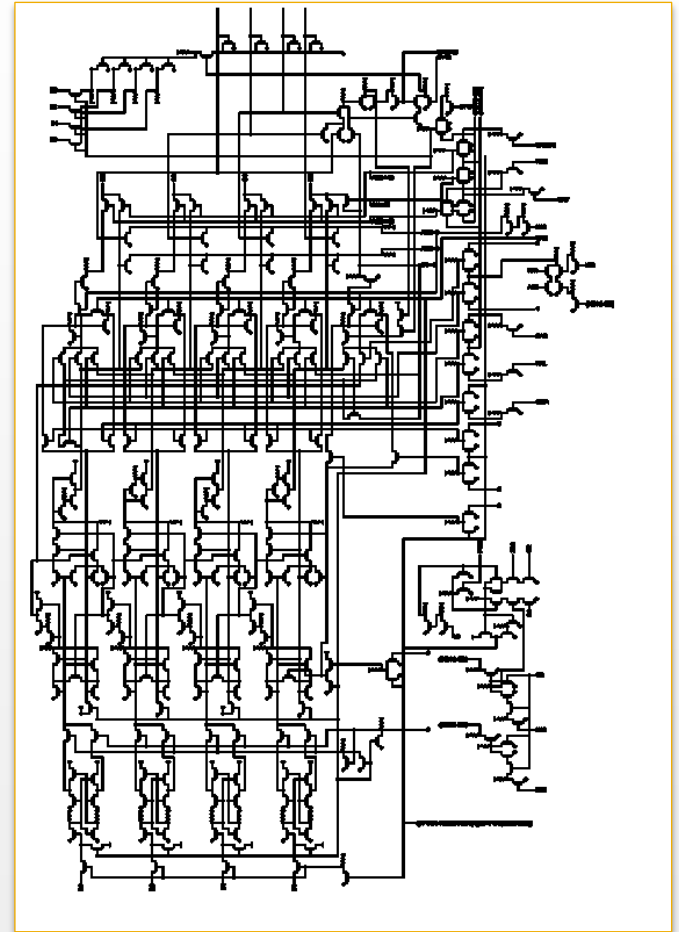
Intel 4004 Project



Registers

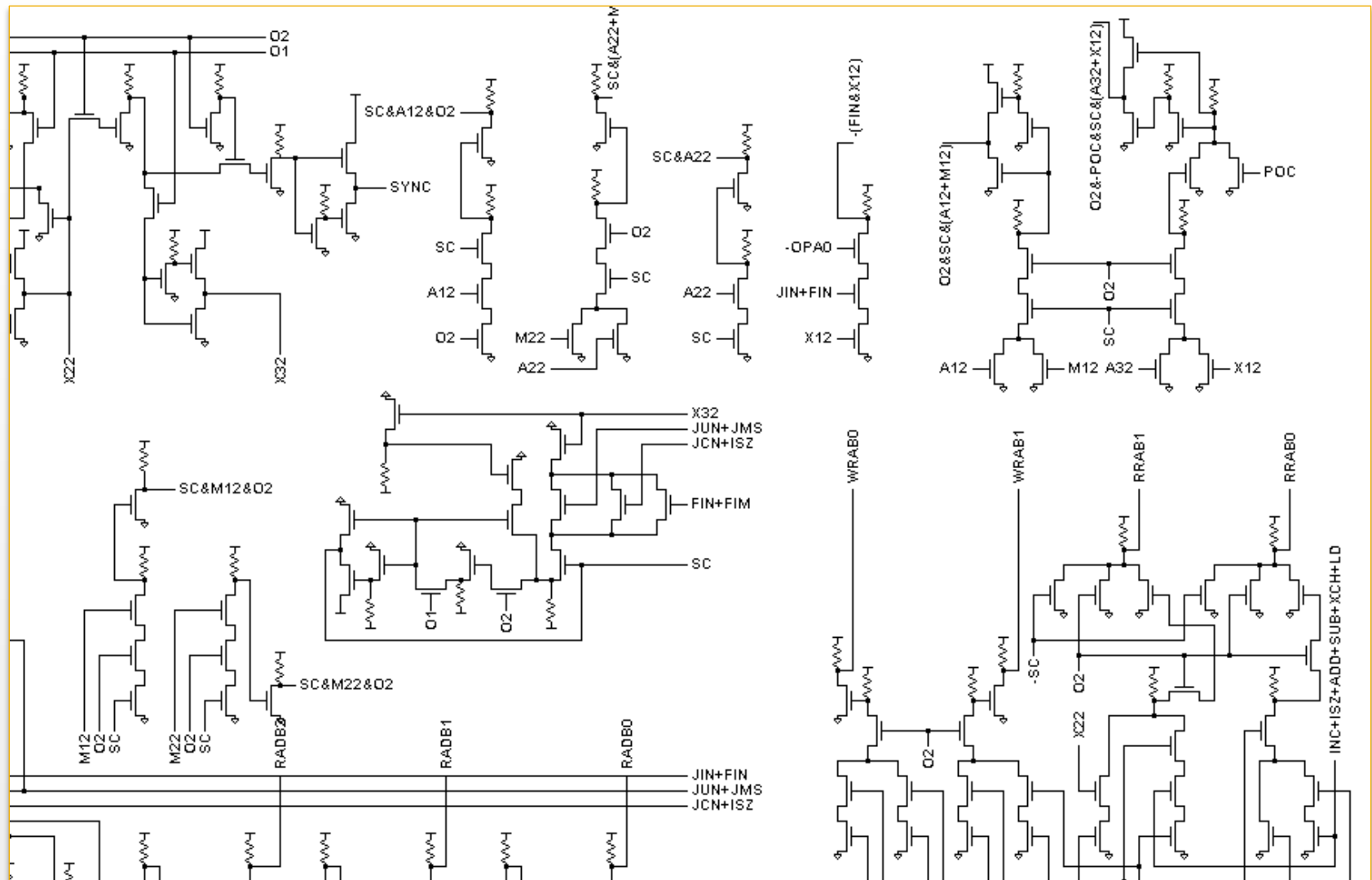


Instruction Decode



ALU

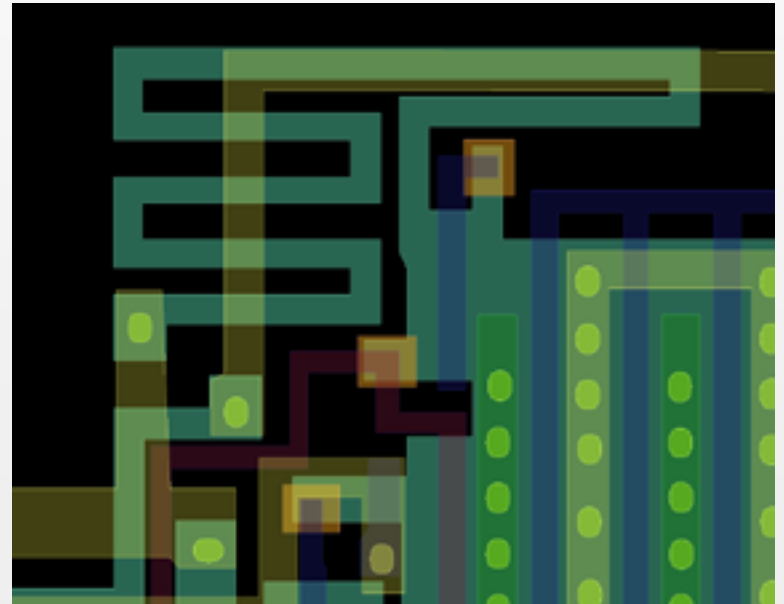
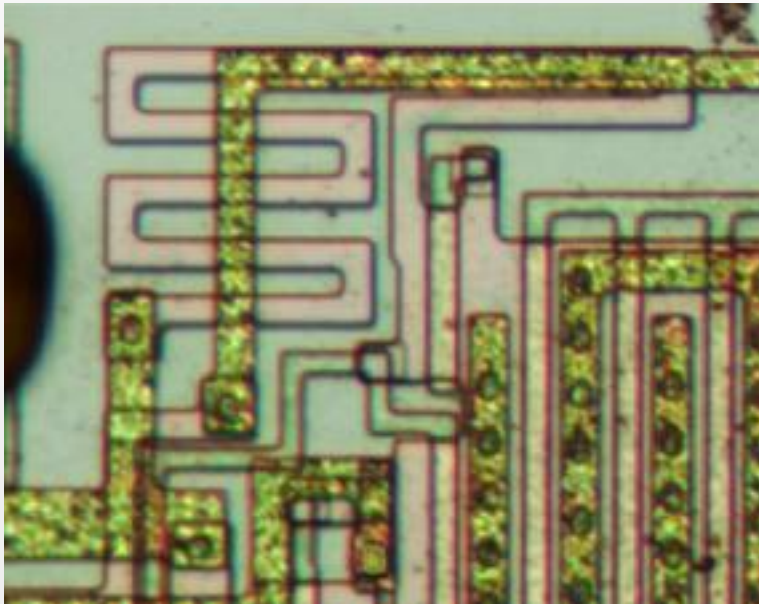
Intel 4004 Project

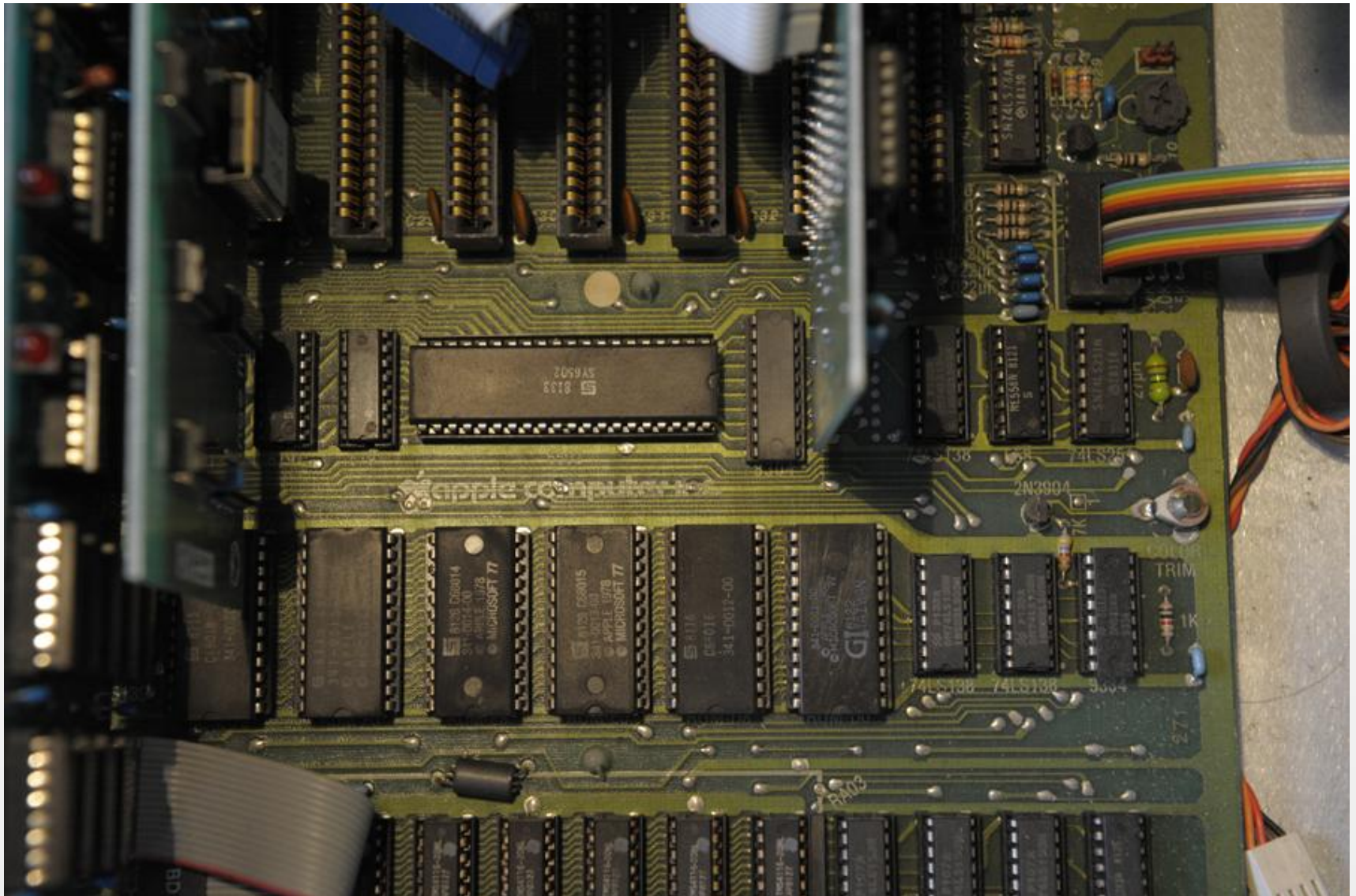


Our Approach

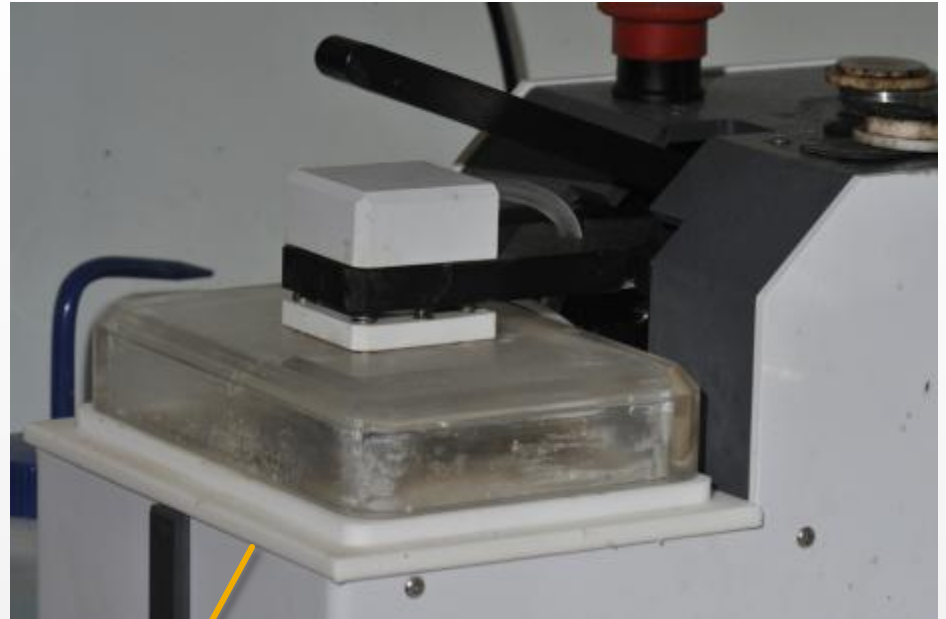
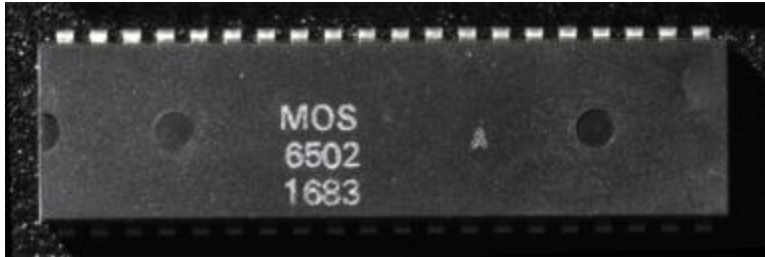


- Model the physical parts
- Polygon model
 - Easy to verify
 - Intersect polygons → working chip

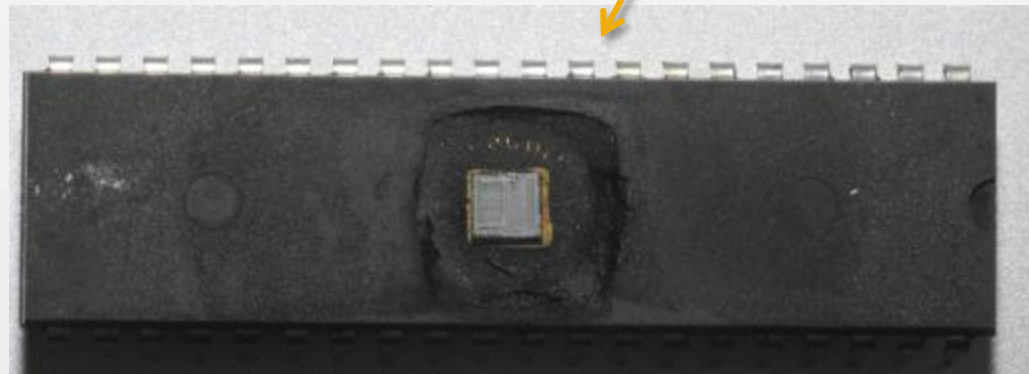




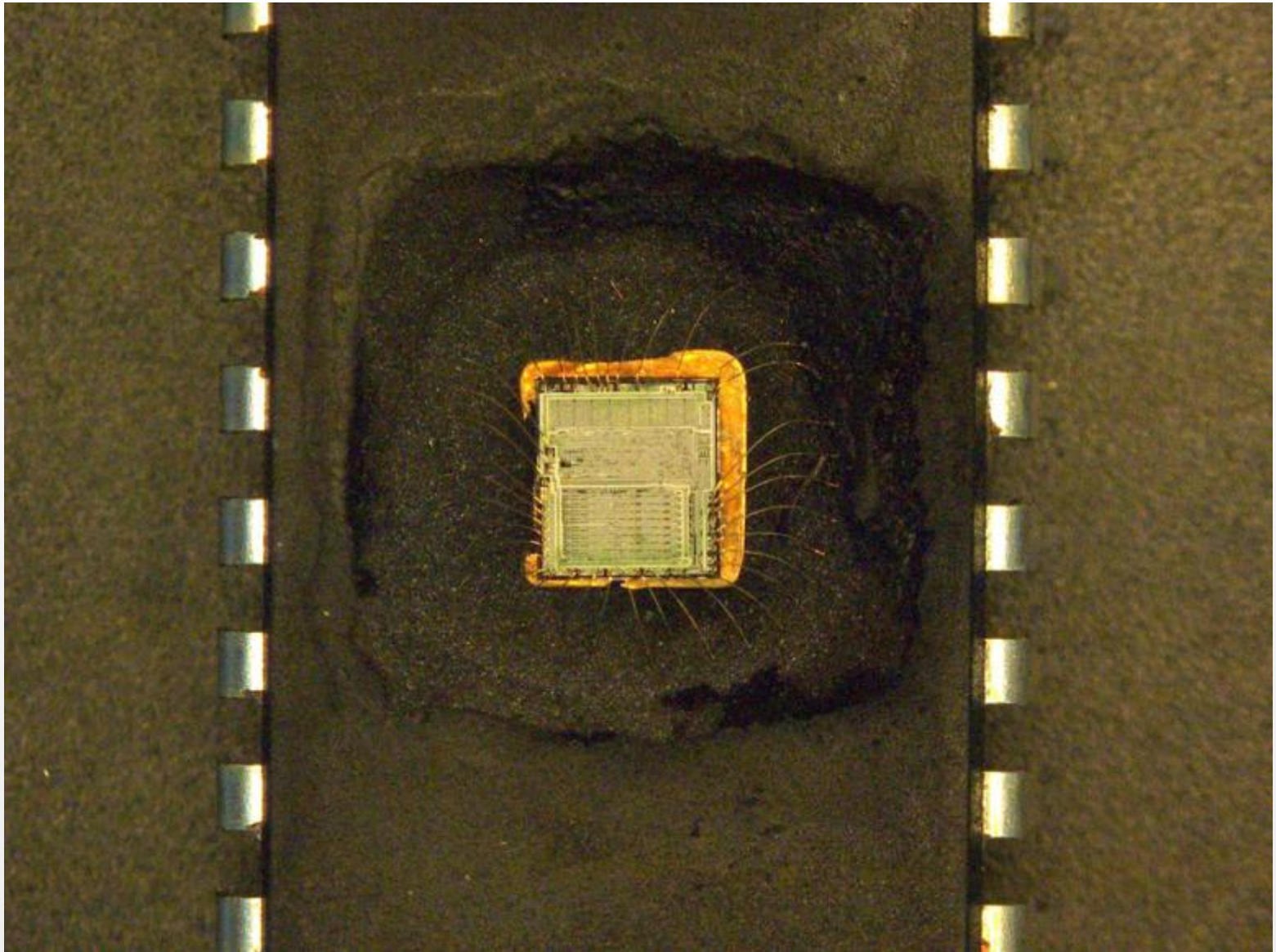
De-capping / de-packaging



Squirts hot sulfuric acid (200° F)



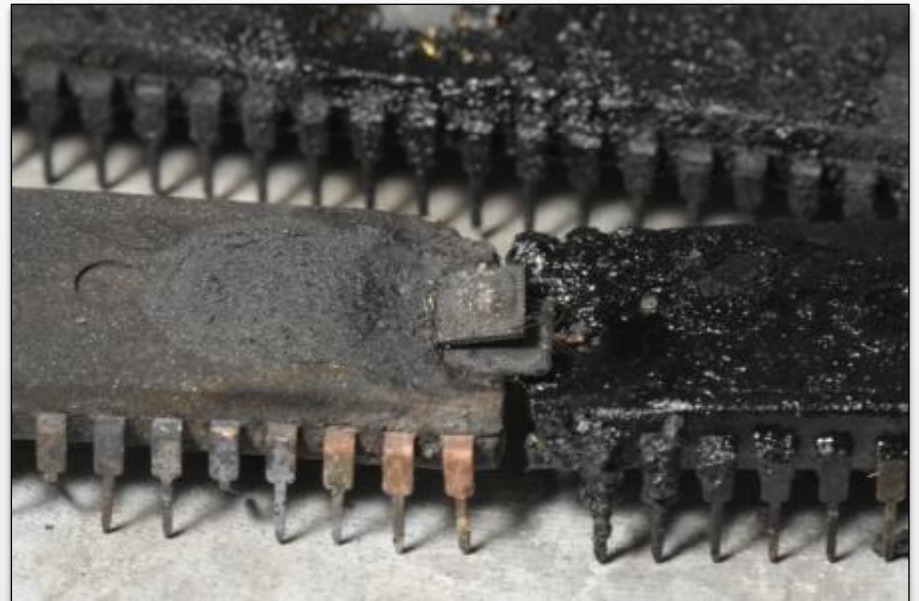
De-capped 6502



Sometimes, not so pretty

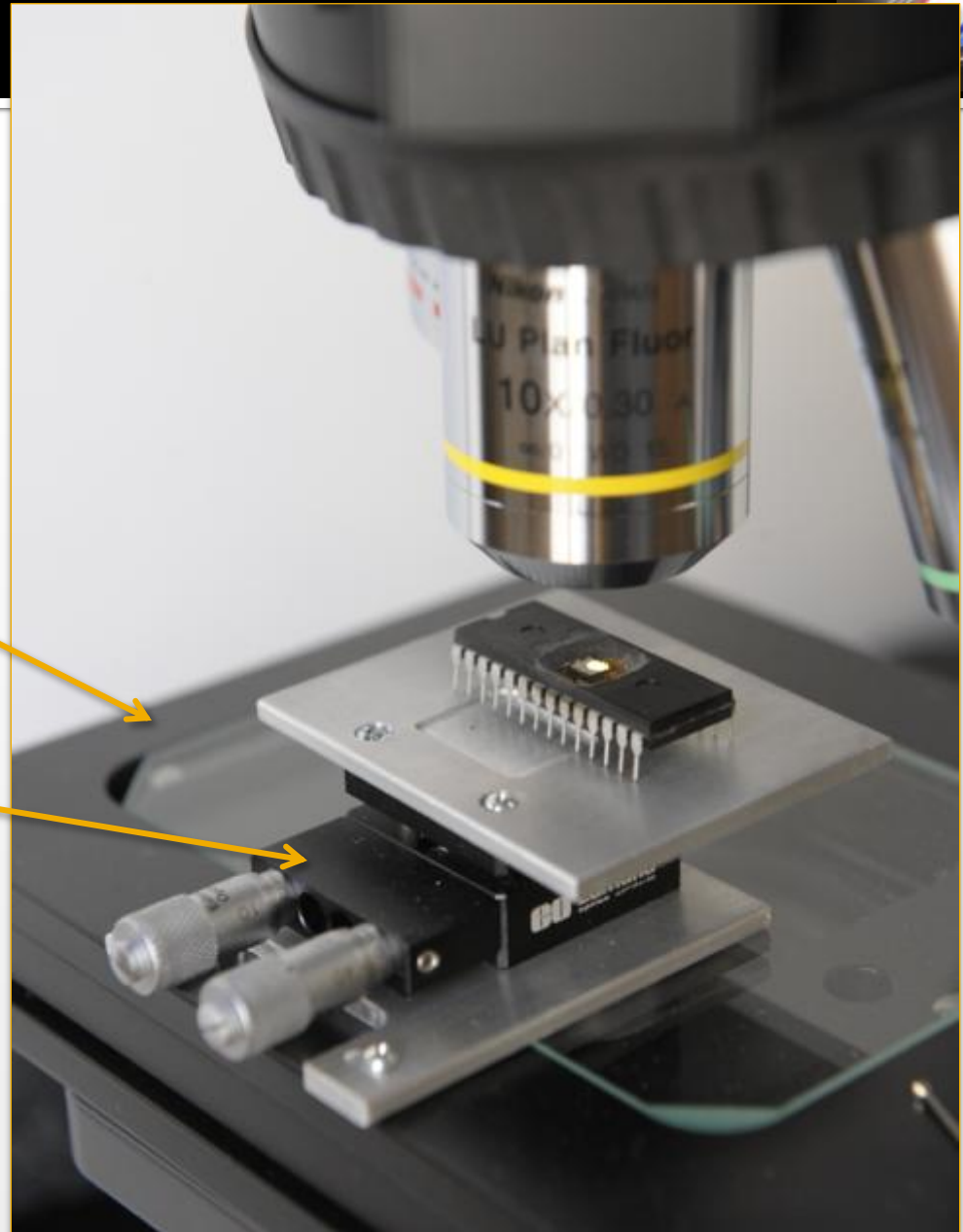


These are still ok
after we clean them up!



Microscopes

- Nikon Optiphot 200
- Nikon LV150
- 5x, **10x**, 20x objectives
- X-Y translation stage to stitch many shots
- Tip-Tilt stage for planar focus

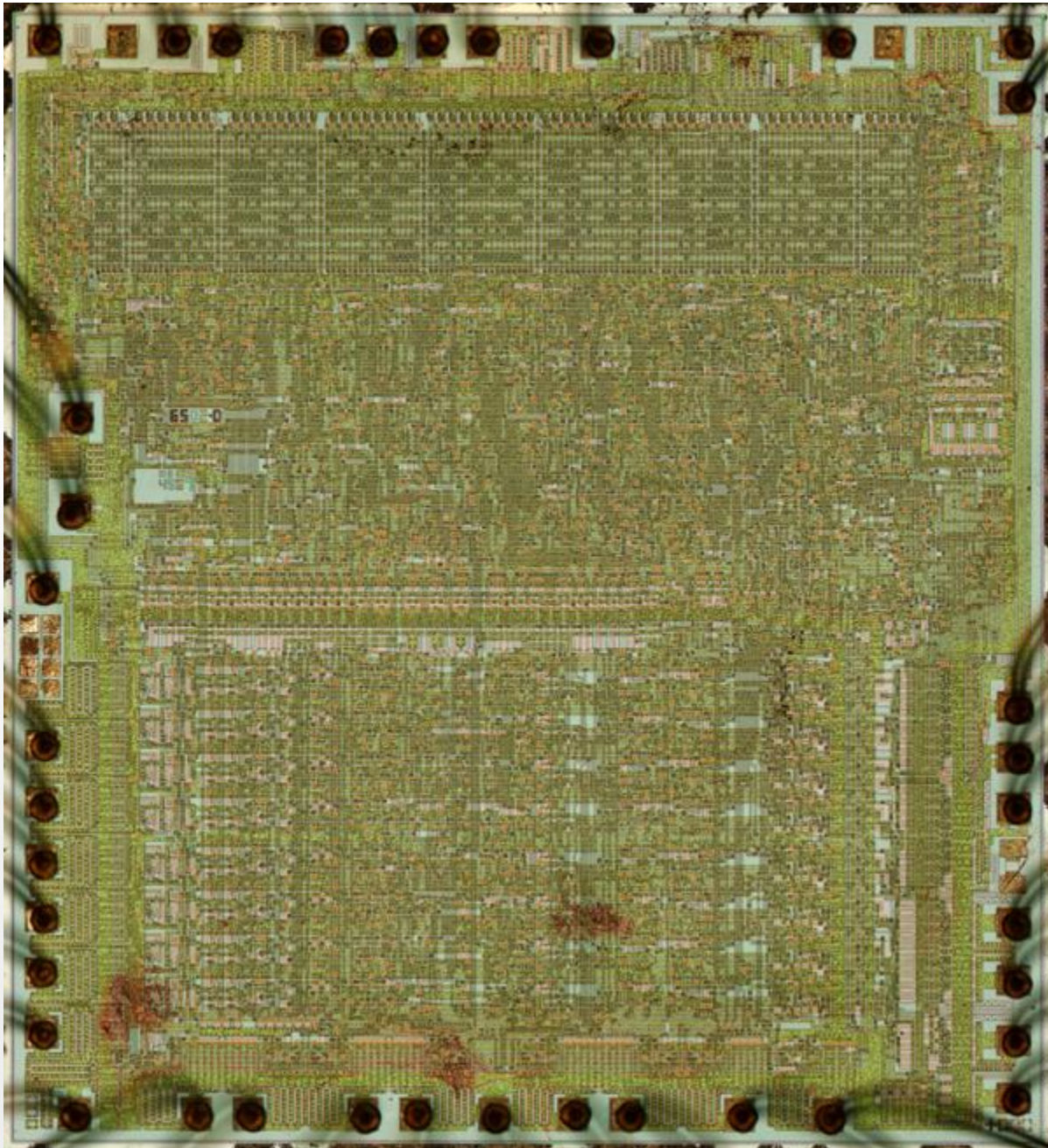


Microscope Shots, 10x objective



- 72 images (8x9 shots) to cover the die
- Align to scope. Good planar objectives





Result:
6502D die shot

18,000 x 19,000 image
342 Mpix

Only need ~6000 x 5800
for what comes next...

Chip Browser

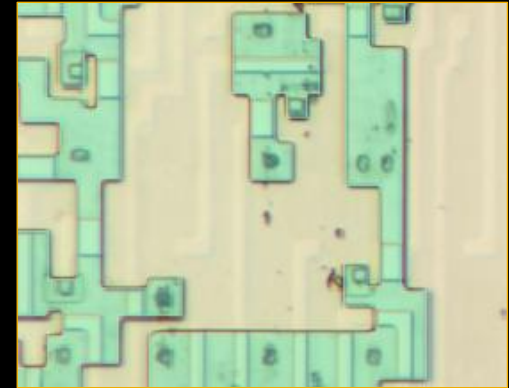
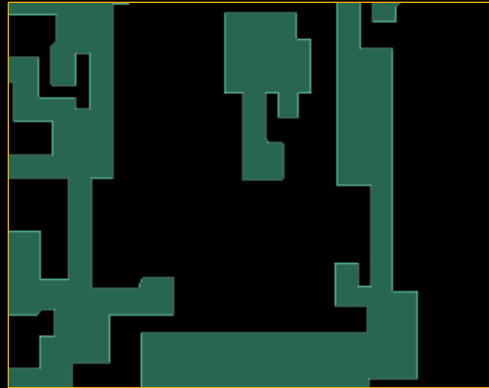
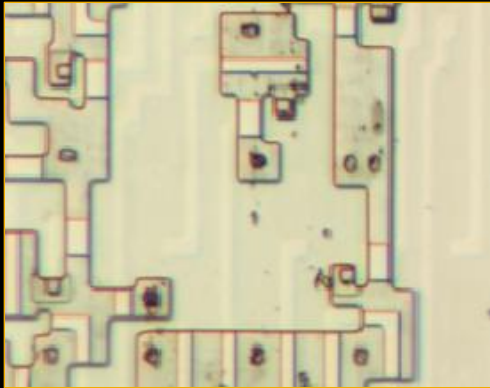


- Demo

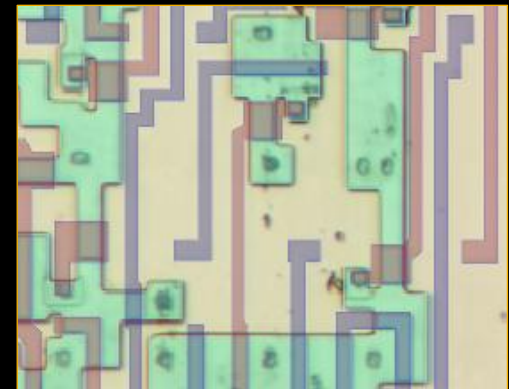
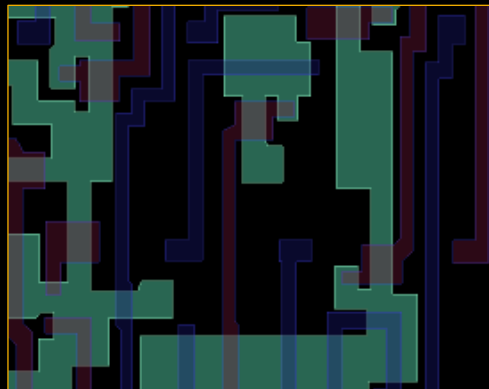
Chip Layers



- Conductive Substrate



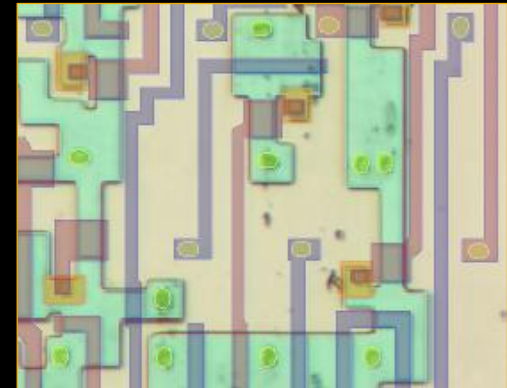
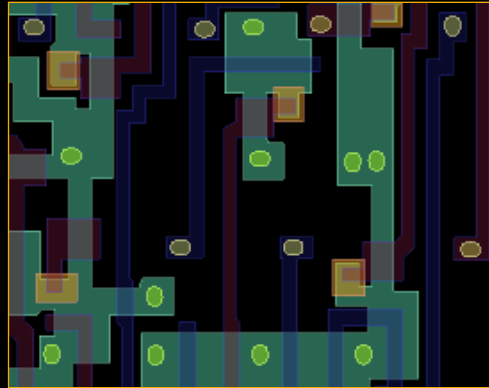
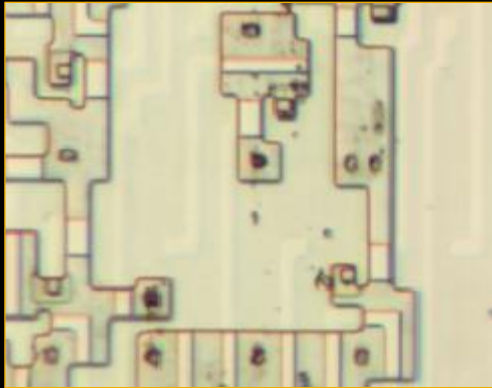
- Transistor-forming wires (polysilicon)



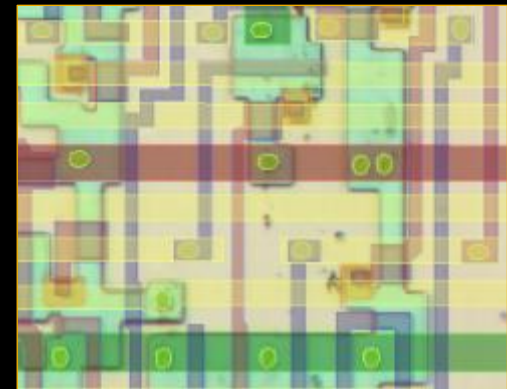
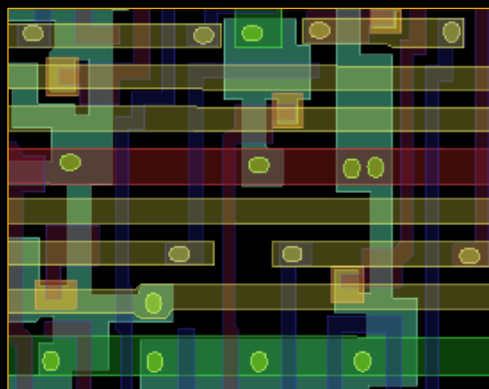
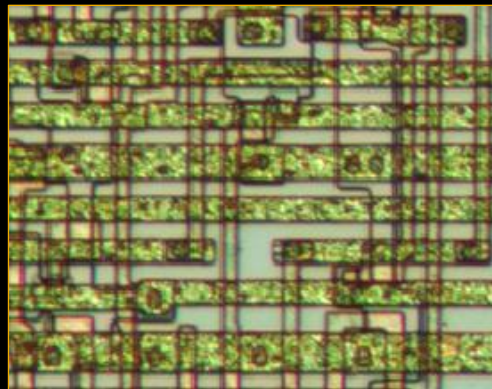
Chip Layers



- Vias and buried contacts



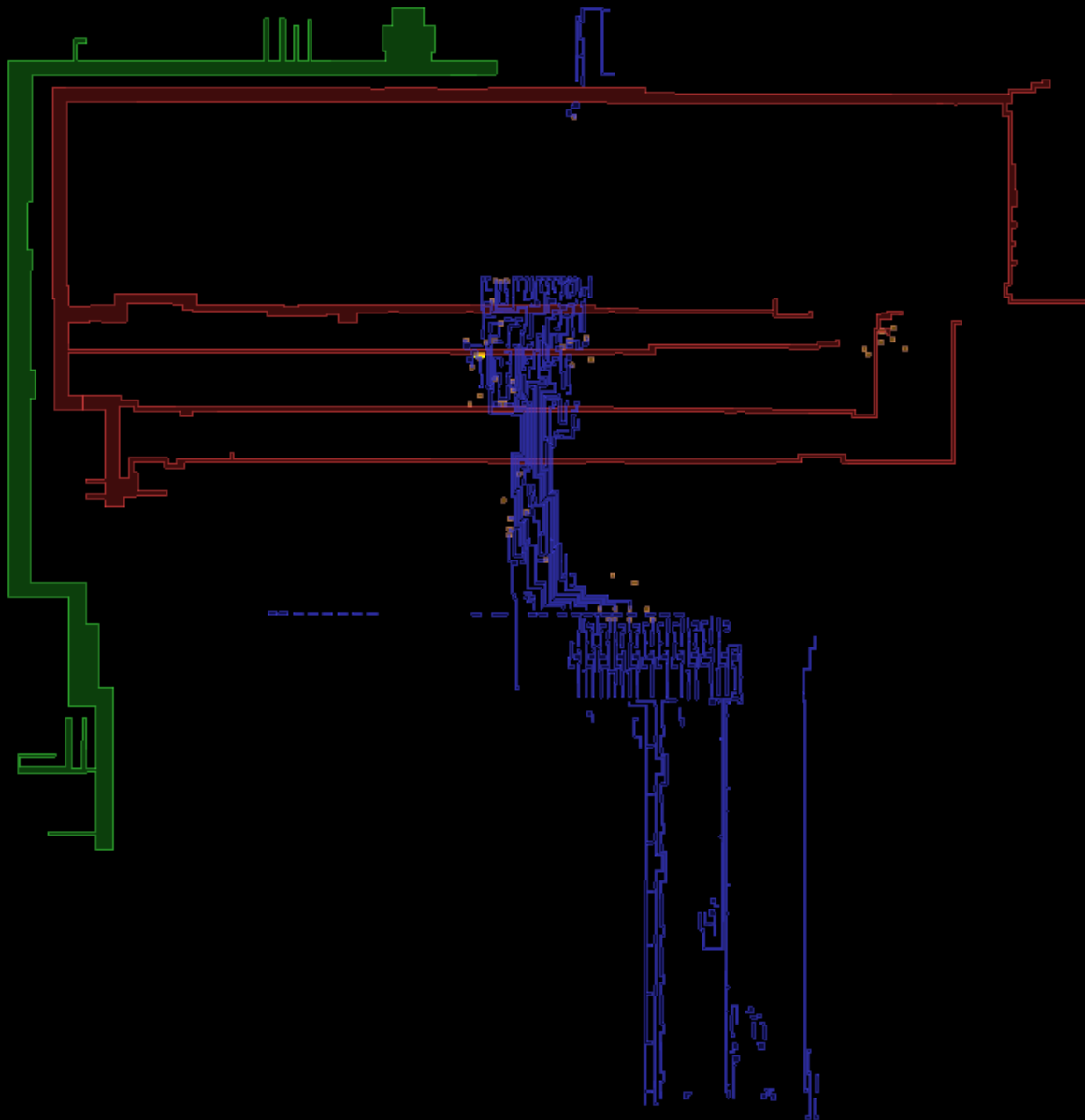
- Metal Interconnects



From Polygons to Simulation

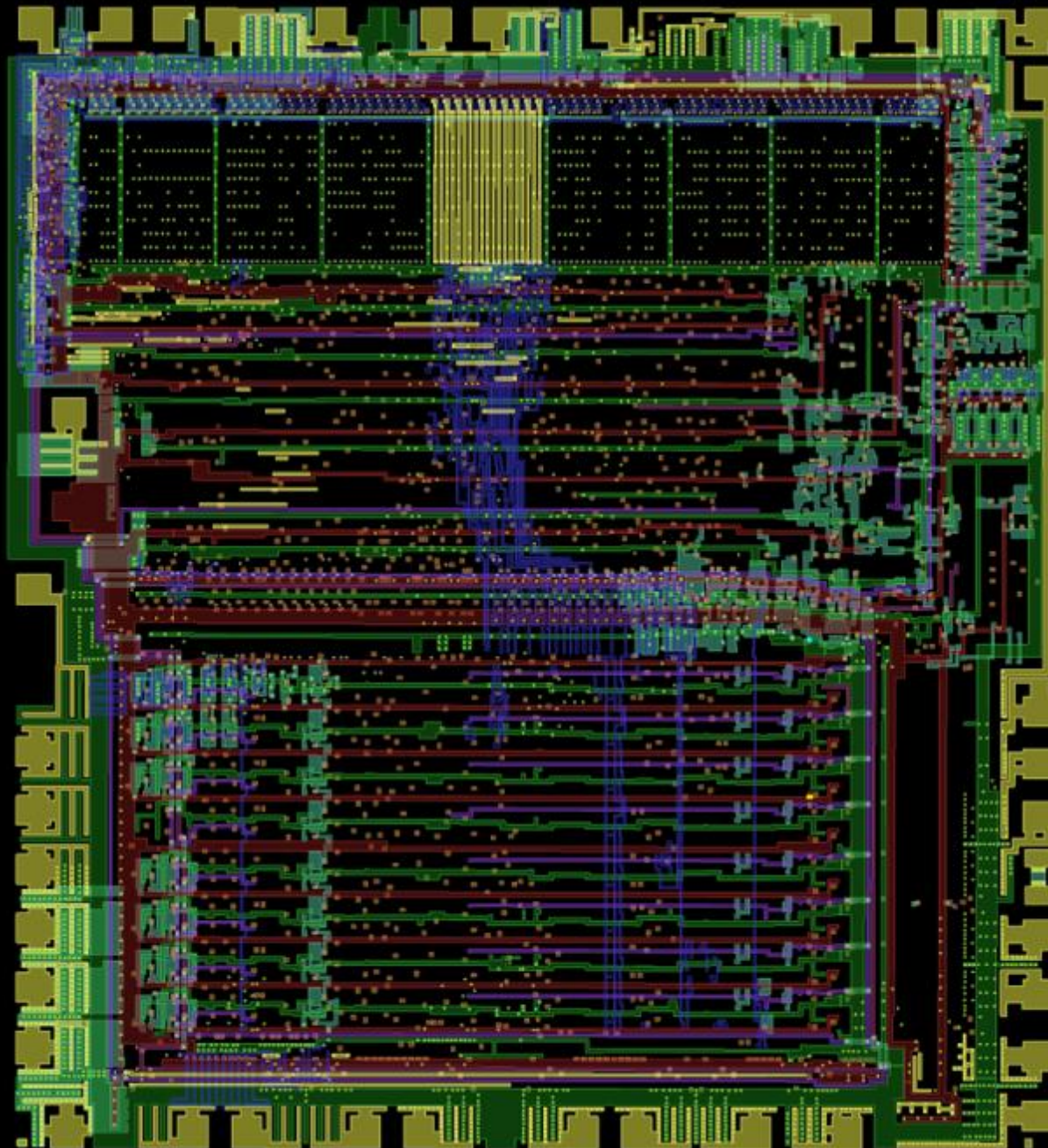


- Demo

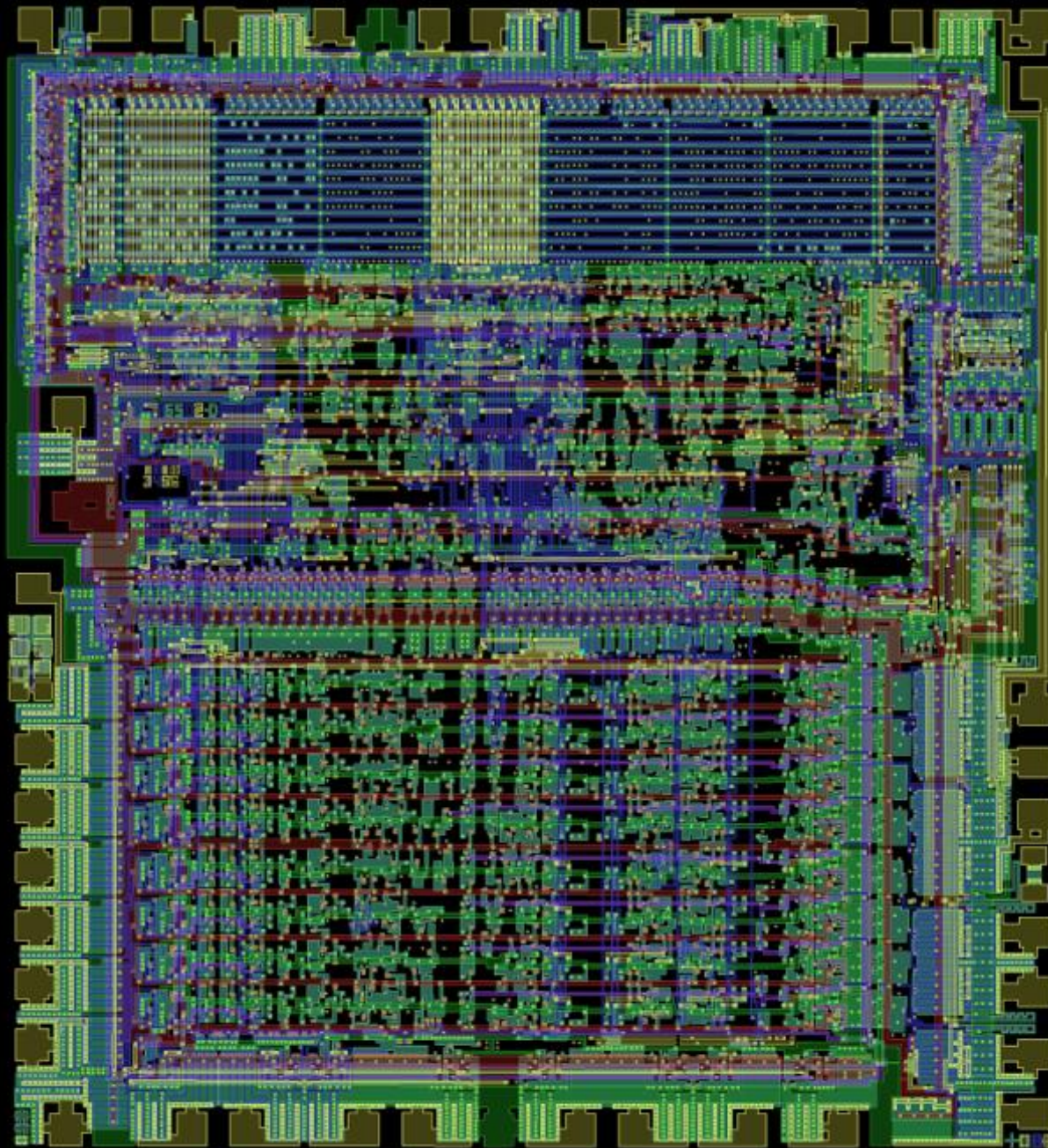


Polygon model
began Nov. 11,
2009

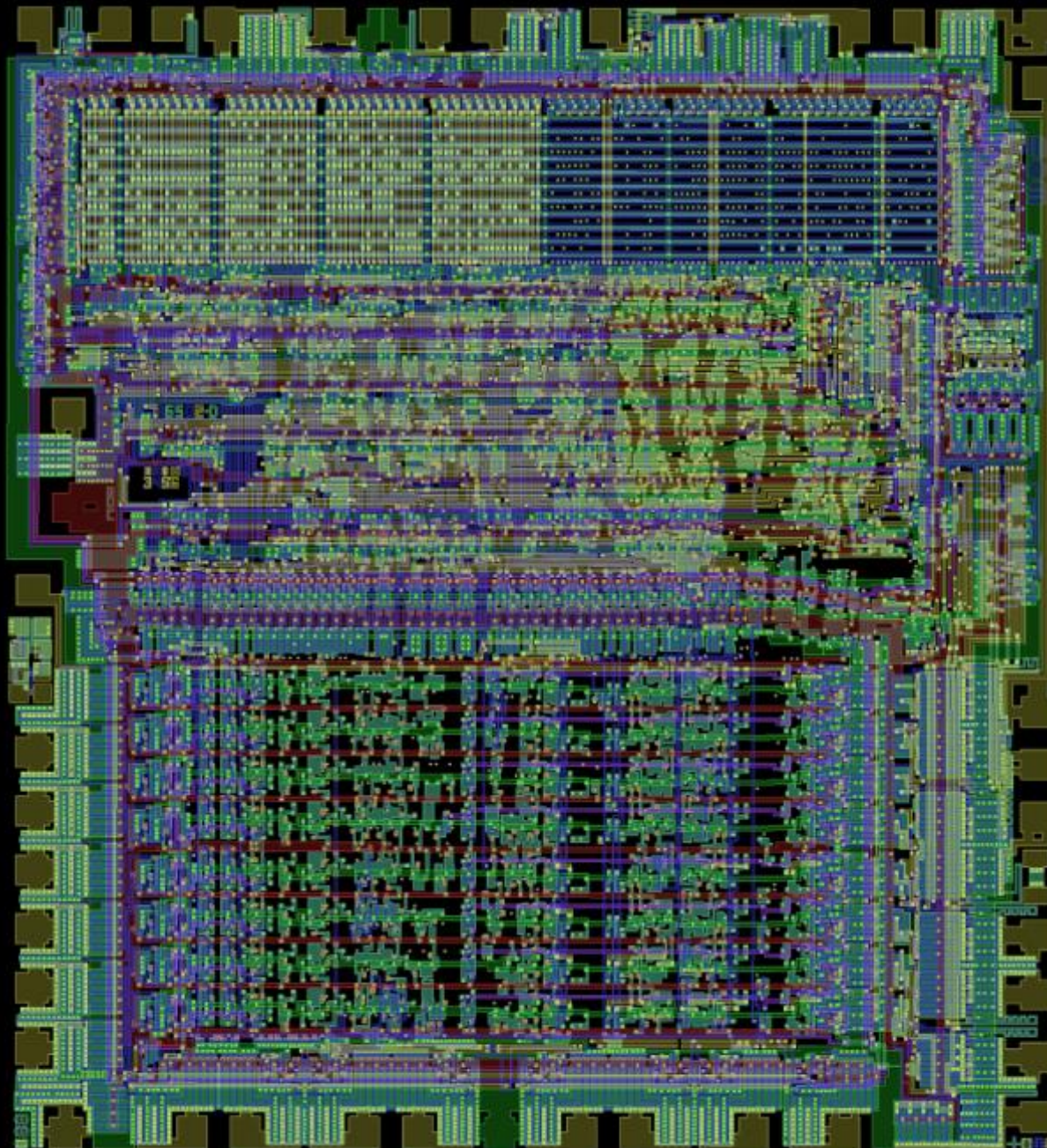
Nov. 16,
2009



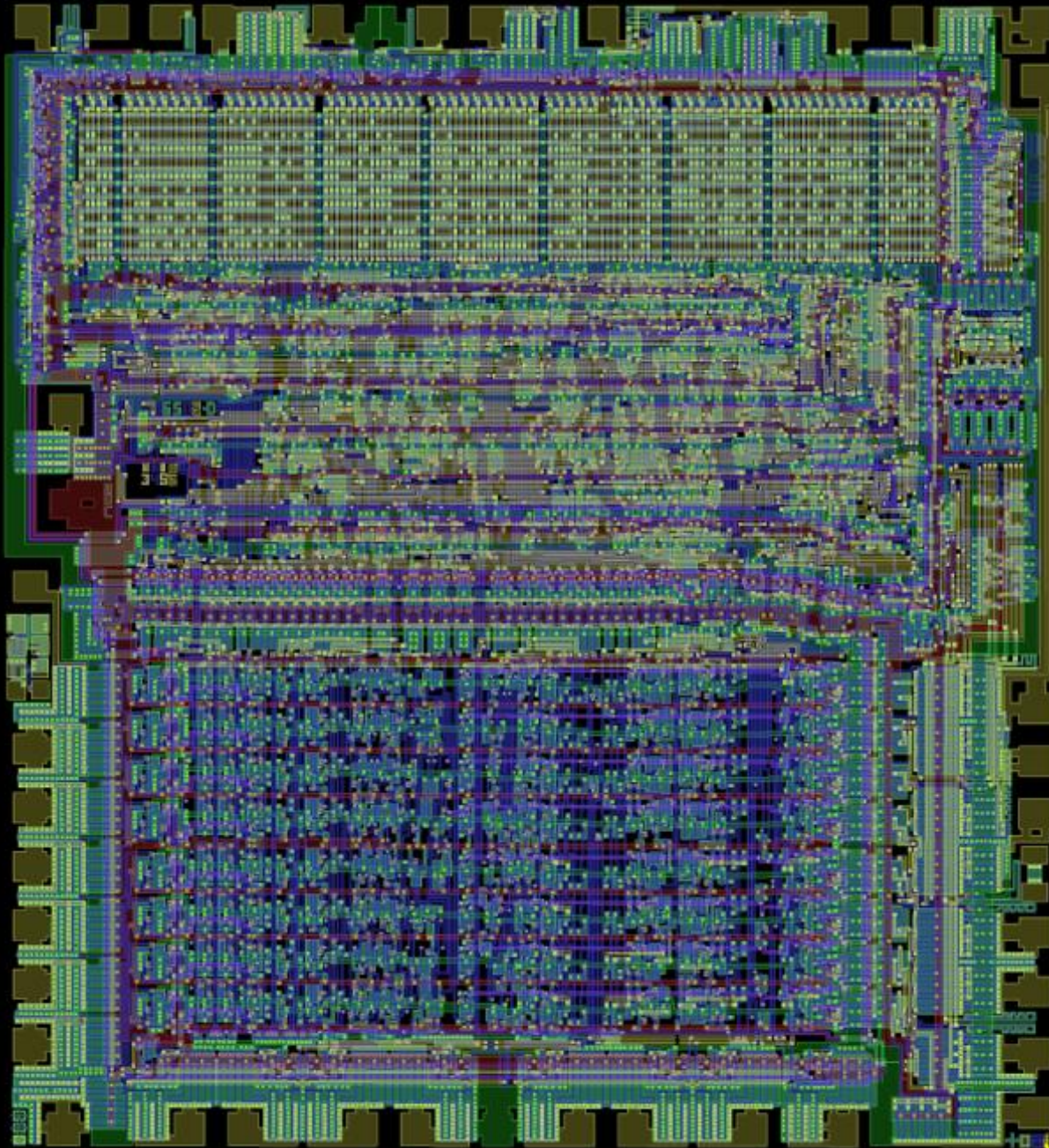
Nov. 23,
2009



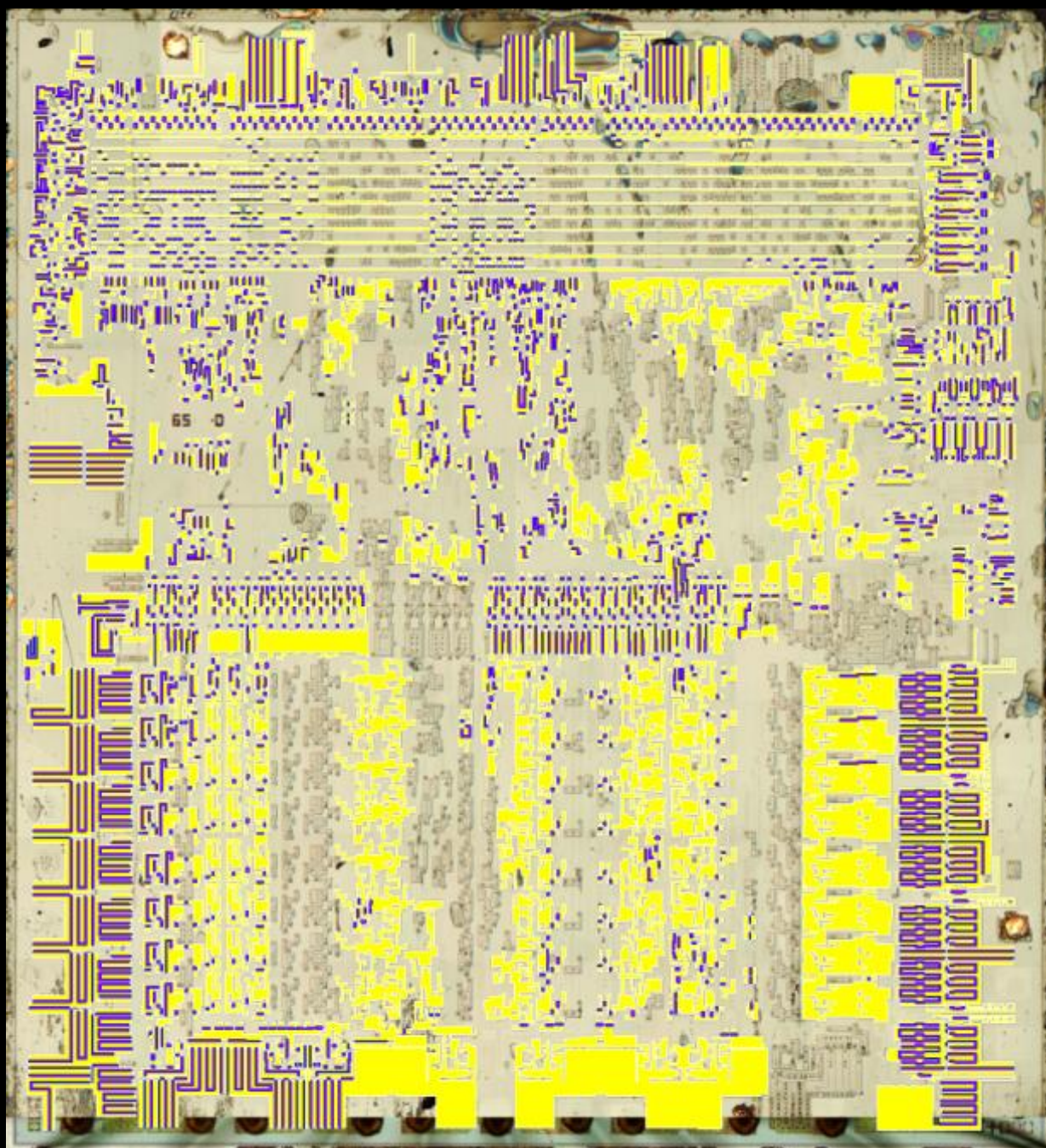
Nov. 30,
2009



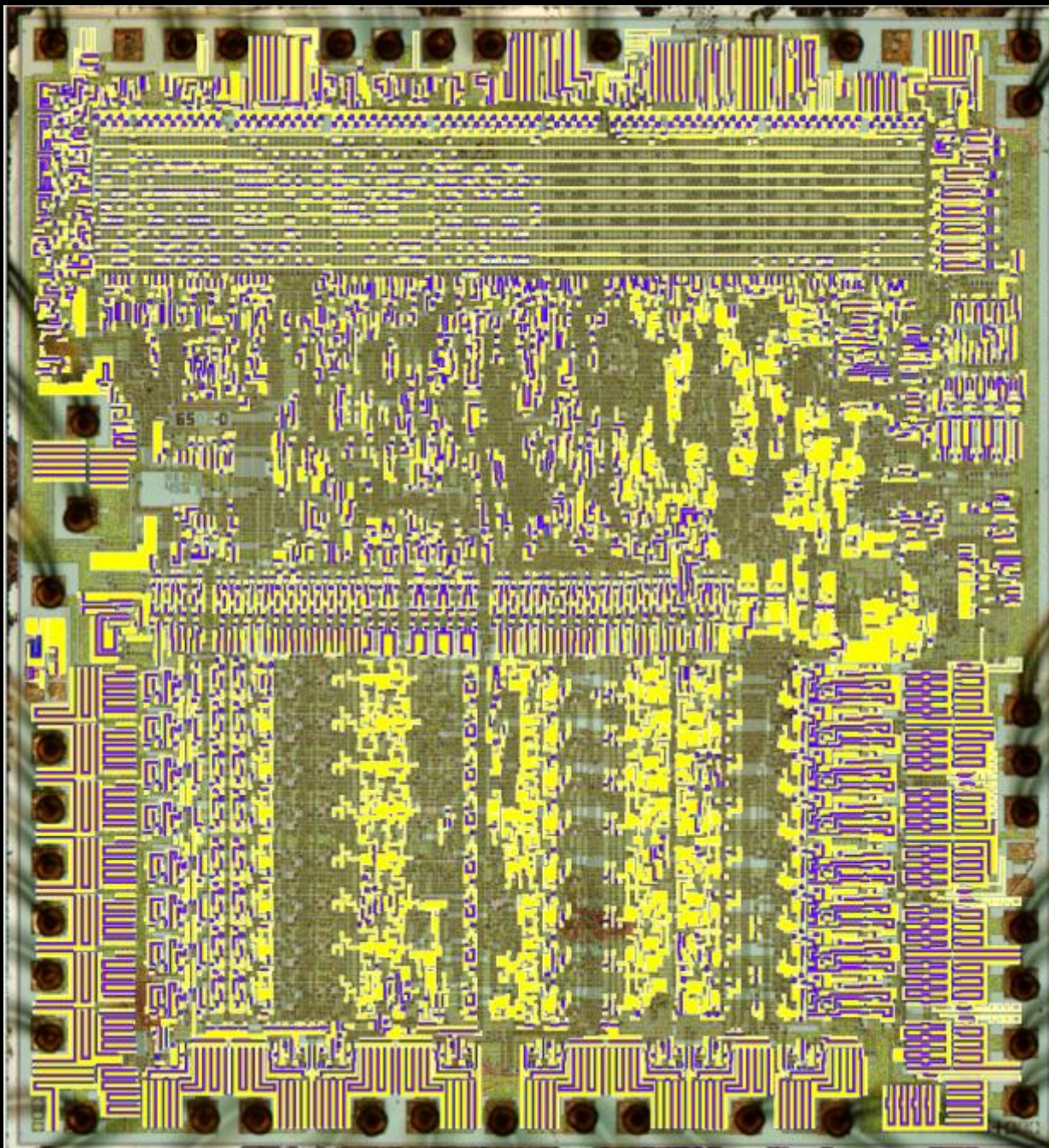
Dec. 4,
2009



Dec. 11,
2009



Nov. 30,
2009



Dec. 4,
2009

Live Demo



- Interactive 6502 chip simulation

Emulation & Simulation

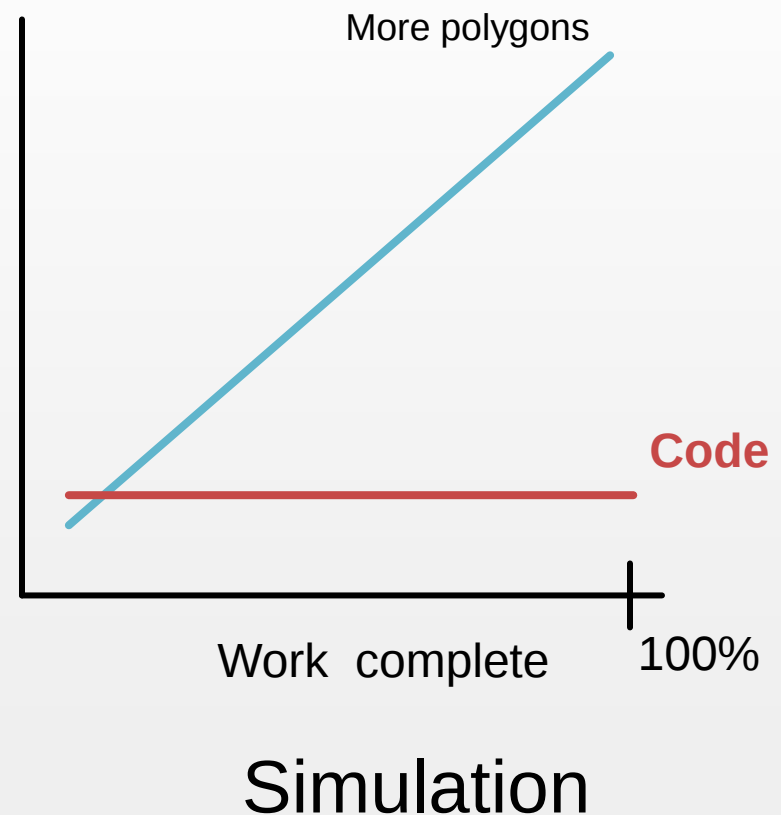
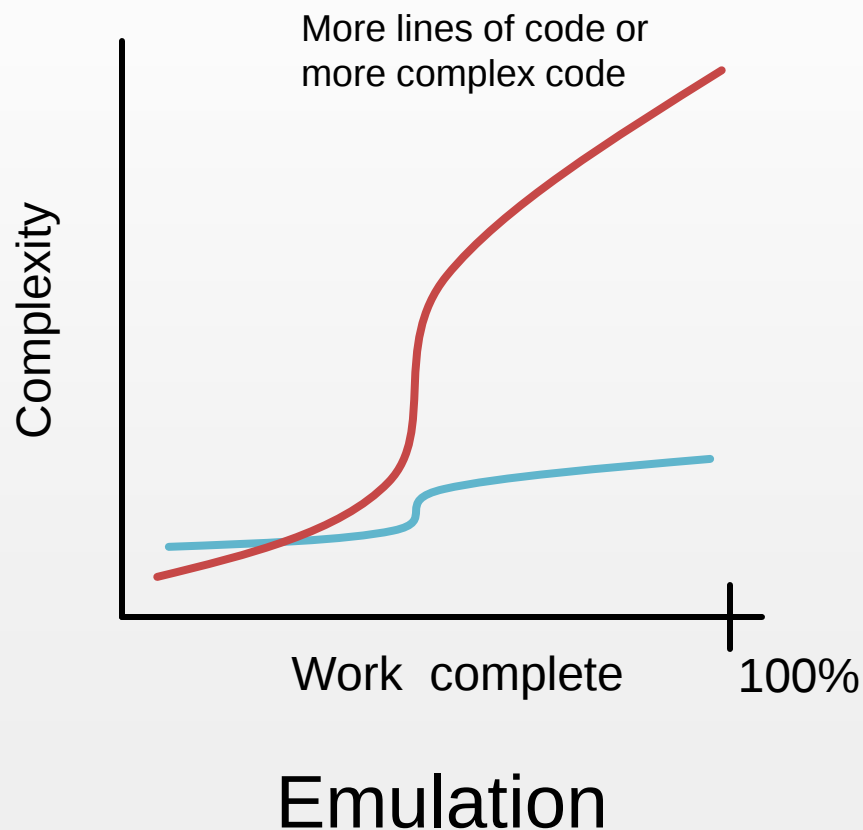


- George Phillips, “Simplicity Betrayed”, Communications of the ACM, Vol. 53 No. 6, pages 52-58. [Full text](#)
- TRS-80 screen display
- Simple characters
 - Byte in memory → character on screen
- Easy to approximate
- Extremely difficult to emulate accurately

Emulation & Simulation



■ Complexity: **Code**, **Data**

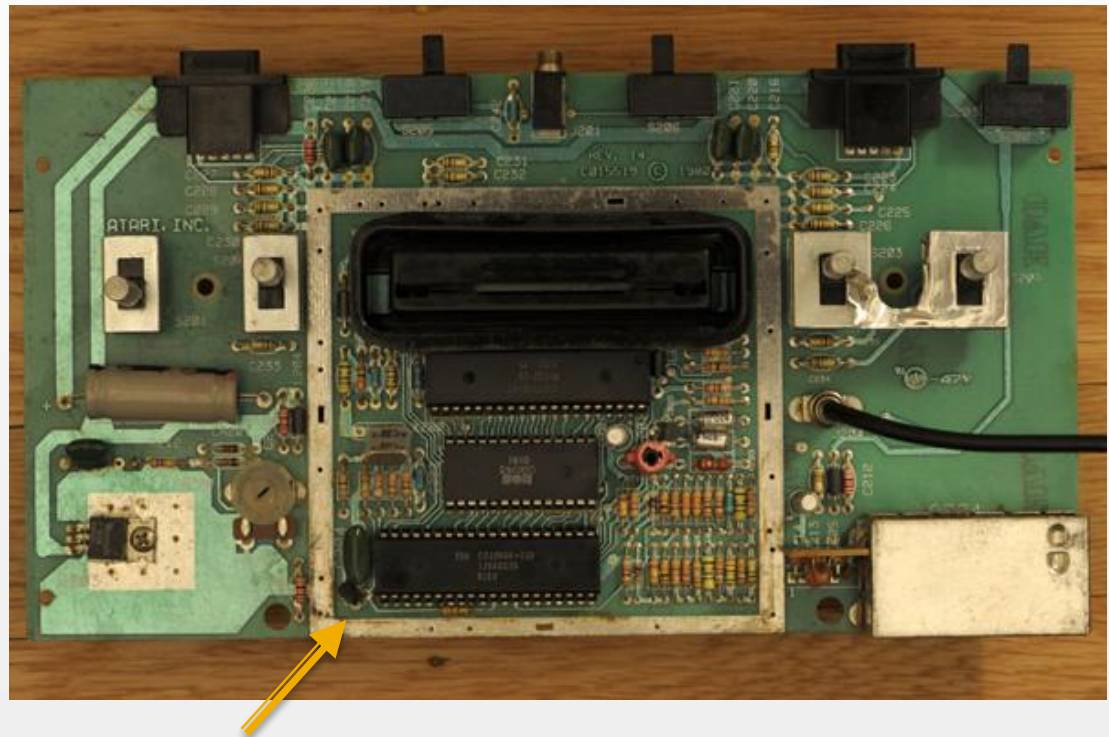


But wait... there's more!



- Verifying bytes is kinda dull
- The 6502 has friends

Atari 2600
game system

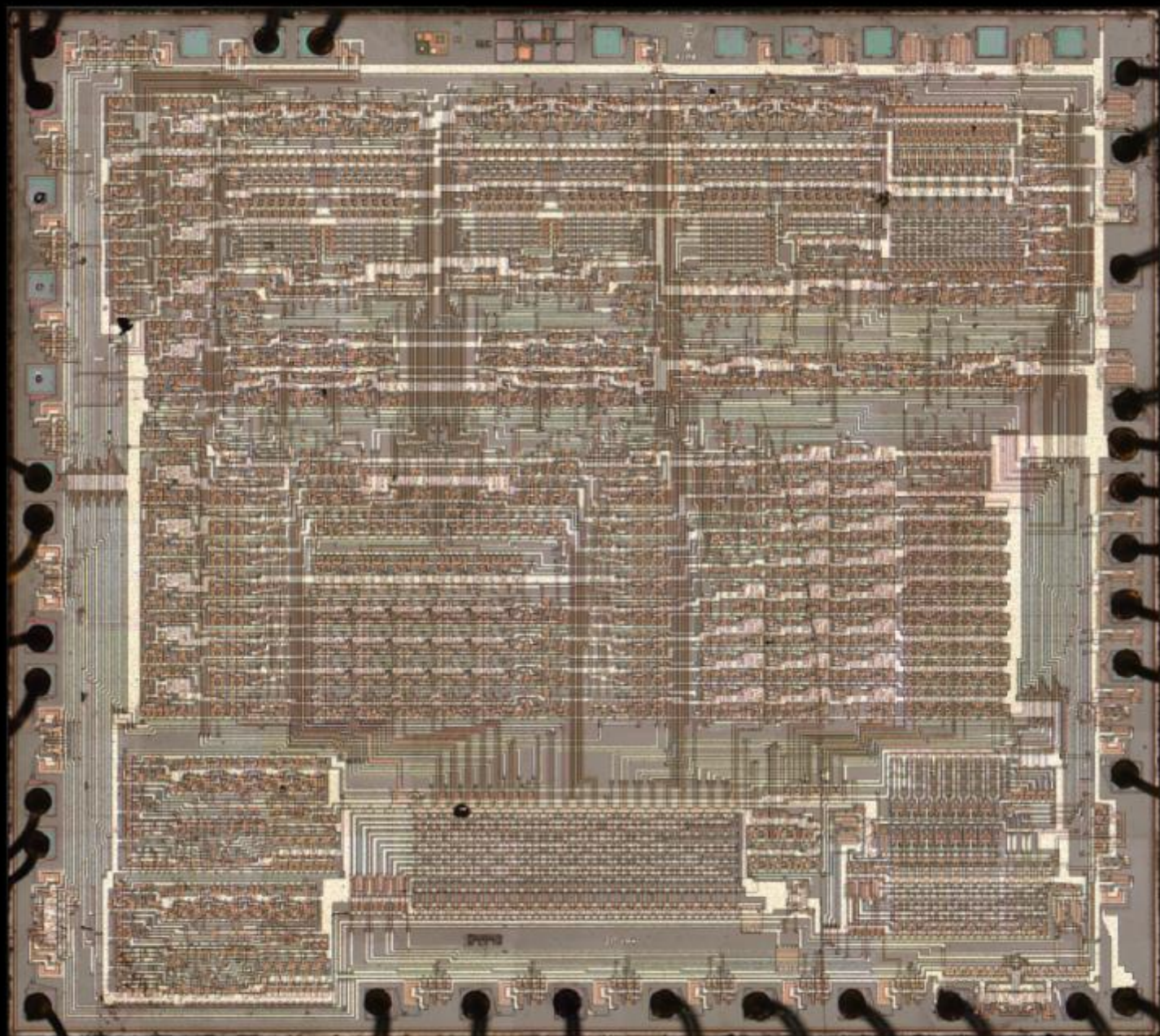


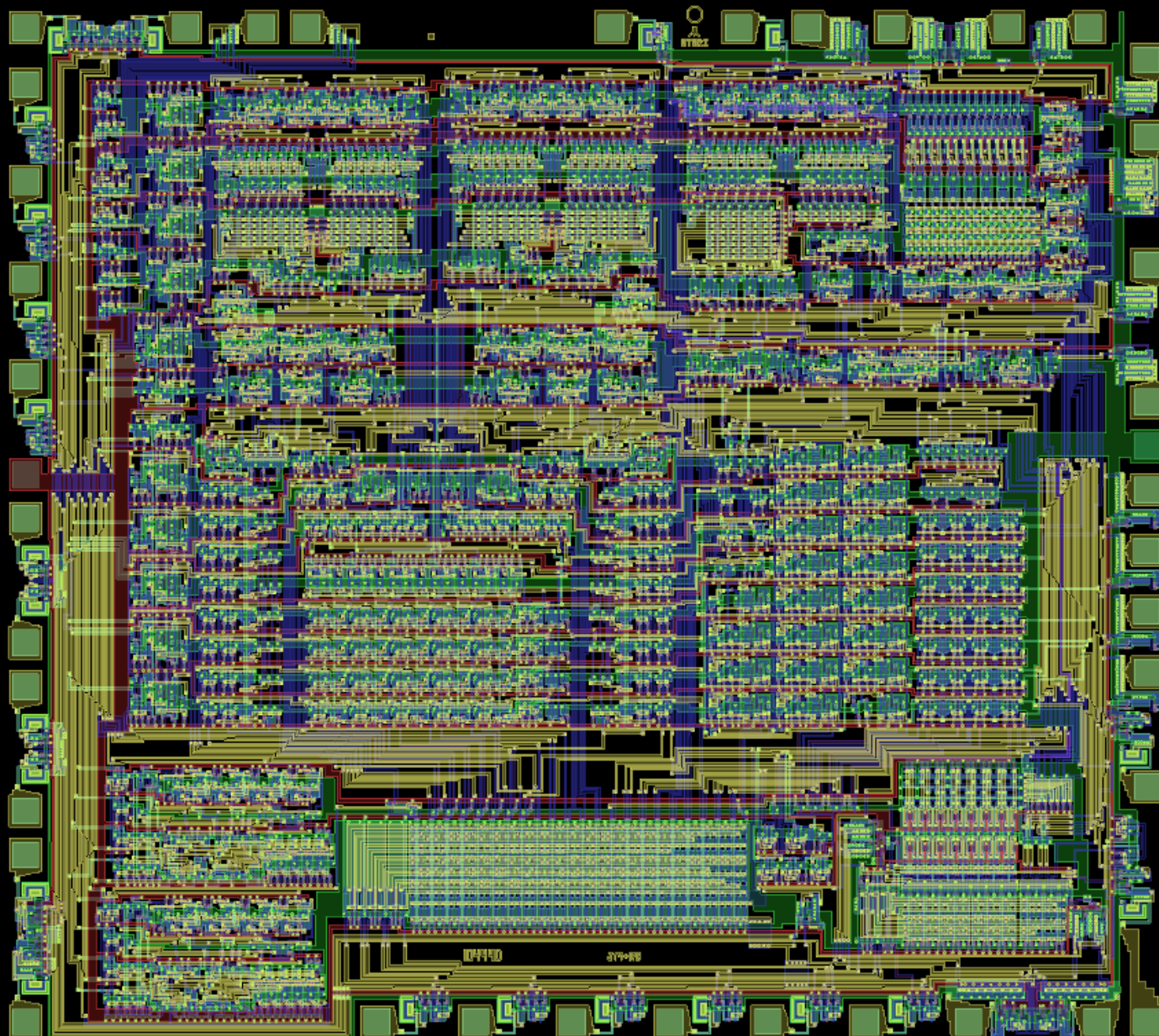
Atari 10444D, aka. TIA (Television Interface Adapter)

Atari TIA



- Makes video signal
 - Made my first pixels 😊
- Sprite engines. No framebuffer
 - Framebuffers cost \$60,000
- We know how it connects to the 6502

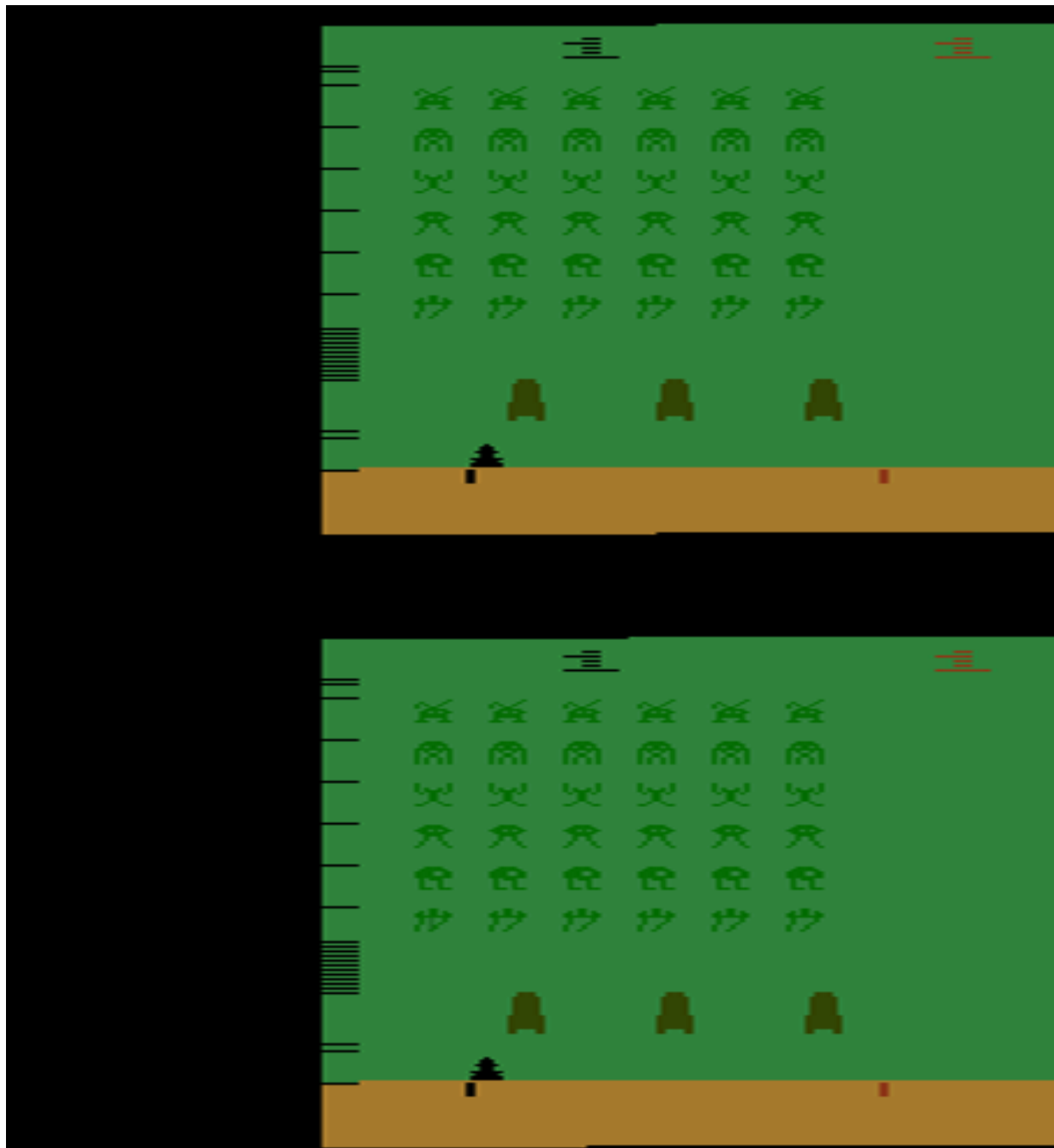




Connect two Chip Simulations

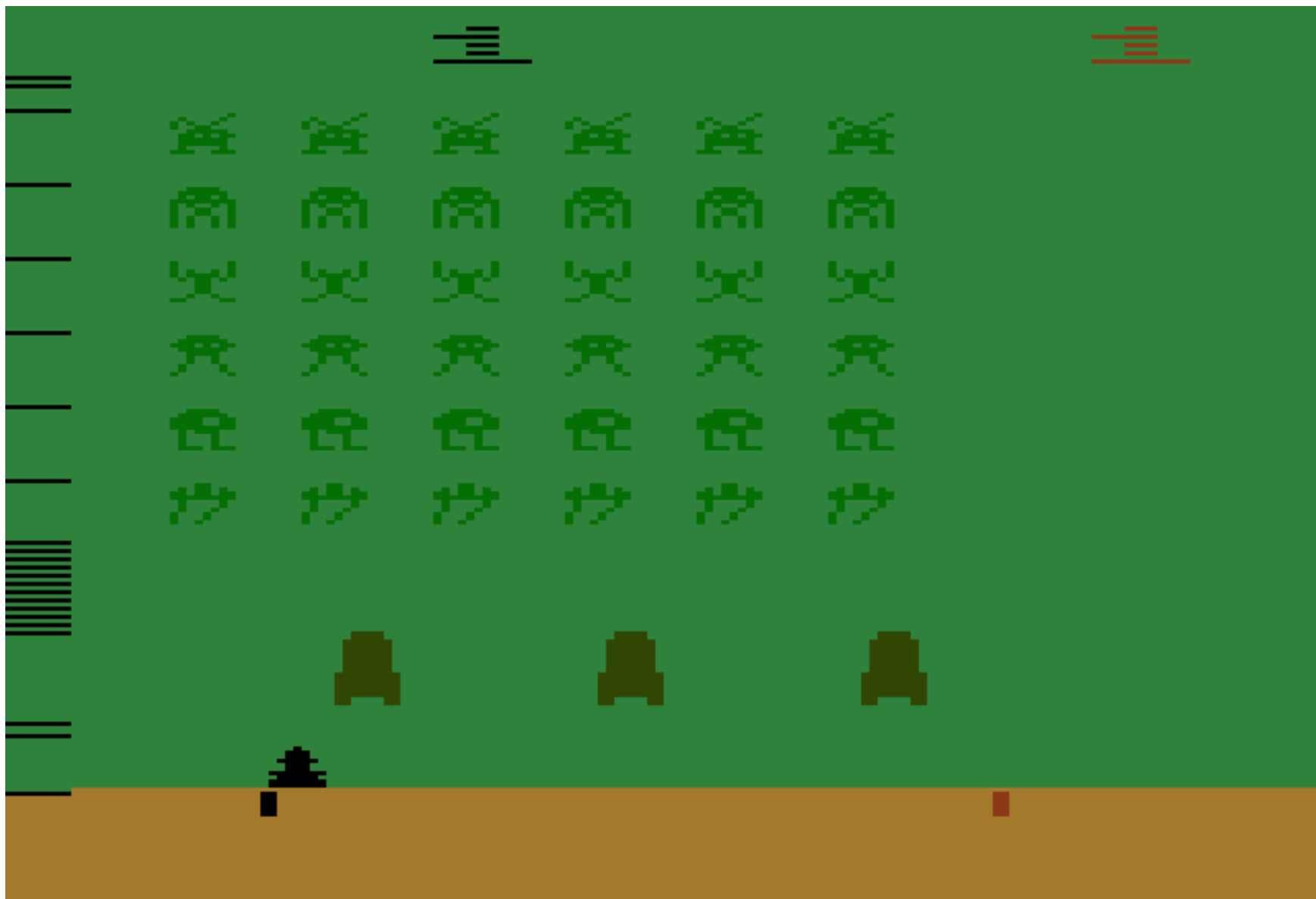


- Emulate program ROM and RAM
 - Feeds the 6502 instructions
- Simulation code toggles the input clock
 - That's all. Just toggle 1 bit
- Read Color and Luminance at each clock



2 frames of video
from combined 6502
and Atari TIA
simulation

Shows h-blank, v-blank



"Space Invaders" from combined 6502 and Atari TIA simulation, 7/23/2010

Stella Emulator





Pitfall, Activision 1982, generated from combined 6502 and Atari TIA simulation
(I do own the cartridge ☺)

Conclusion



- It's EASY to preserve historic hardware
- Parallelizable
- Guide for emulation
- Work from transistor-level simulation to coarse fast simulation?
- Lots more to do!

Download, Contribute!

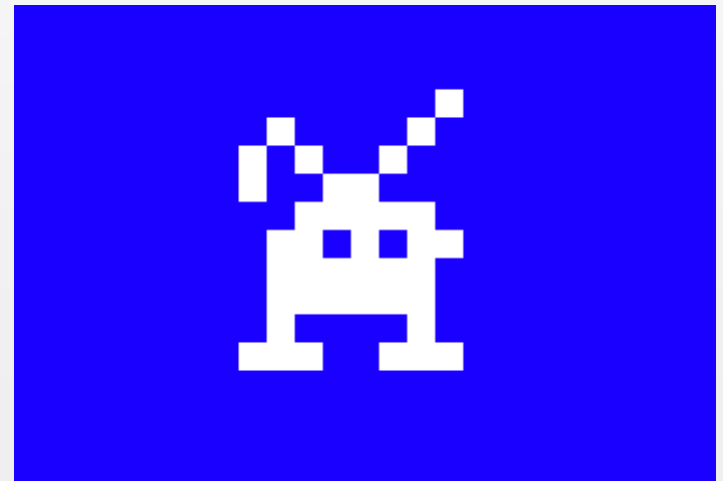


- Free for non-commercial use
- www.visual6502.org
- I'm late – nothing up there yet =/
- Check in a week or two

Many Thanks



- Barry Silverman, Brian Silverman
- Jason and Irene Sutton. Gordon James
- Howard Marks. Steve Scott
- William Mensch, Jr.
- Anya Gershenzon
- Chris Twigg. Alex Suter
- www.6502.org archives
- ... and all the people behind our first pixels!



Output of our combined 6502 and TIA simulation

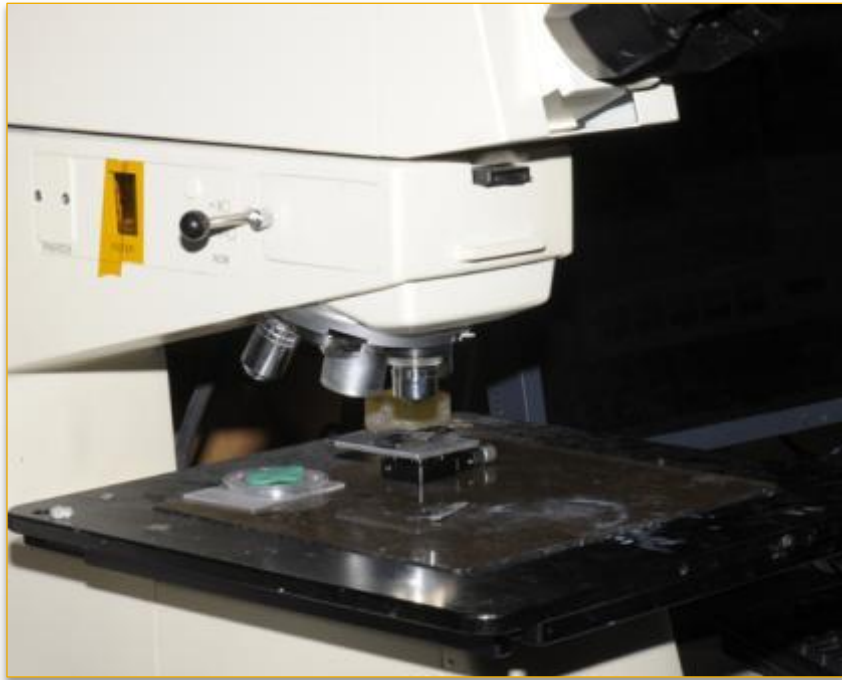
Bibliography



- George Phillips, "Simplicity Betrayed," Communications of the ACM, Vol. 53 No. 6, Pages 52-58
- Andrew Volk, Peter Stoll, Paul Metrovich, "Recollections of Early Chip Development at Intel", Intel Technology Journal Q1, 2001
- Tim McNemey, Intel 4004 Project, <http://www.4004.com>
- Erik Klein, <http://www.vintage-computer.com>
- "Stella" Atari 2600 emulator. stella.sourceforge.net
- Wikimedia Commons. www.wikipedia.org



Microscopes



Nikon Optiphot 200
5x, **10x**, 50x, 100x objectives

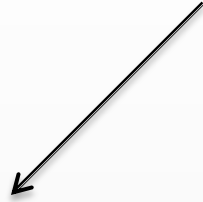


Nikon LV150
5x, **10x**, 20x objectives

Which CPU?



- Motorola: 6800 – 6809 – 68000 – 68040



- MOS: 6502 – 6507 – 6510

- Intel: 4004 – 8008 – 8080 – 8085 – 8086 – 80186, x286

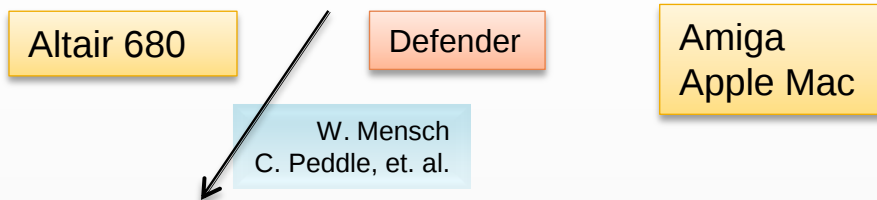


- Zilog: Z80 – Z8000 – Z80000 – Z380

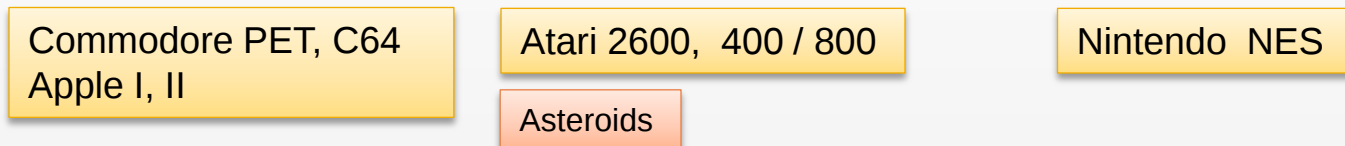
Which CPU?



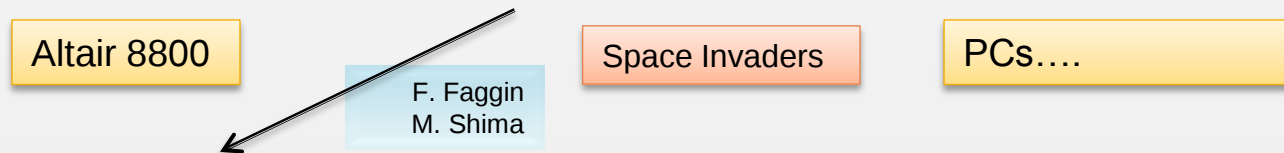
- **Motorola:** 6800 – 6809 – 68000 – 68040



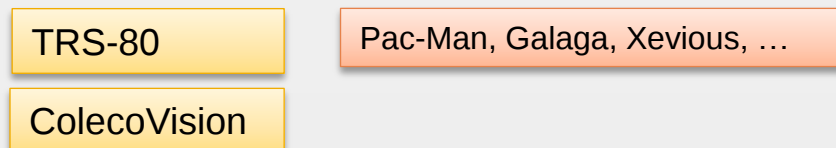
- **MOS:** 6502 – 6507 – 6510



- **Intel:** 4004 – 8008 – 8080 – 8085 - 8086 – 80186, x286



- **Zilog:** Z80 – Z8000 – Z80000 – Z380



6502 Project Timeline



- Start drawing: Nov. 11, 2009
- Finish drawing: Dec. 12, 2009
- Good startup in sim: Dec. 26, 2009
- 2nd gen sim, and verif.: through May 2010
- 100% accurate 6502 in simulation
 - Could make an actual chip
 - No guesswork. Complete information
- Simple code
- Lots of polygons

Vectorization



- Intersect polygons to form:
 - Transistors
 - What they switch together
 - Wires that drive transistors
 - Input to full chip simulation engine
- Result: 100% accurate working chip
 - Timing, cycle counts,
 - Without having to know a thing about CPU instructions
 - Without having to transcribe specs

Apple I: 6502 CPU



Byte into an Apple \$666.66*
* includes 4K bytes RAM

BREADBOARD AREA

CRYSTAL CONTROLLED TIMING

COMPLETE VIDEO TERMINAL ELECTRONICS

LOW-PROFILE SOCKETS ON ALL IC'S

FIRMWARE IN PROMS

KEYBOARD INTERFACE

6502 MICROPROCESSOR

8K BYTES RAM

EXPANSION CONNECTOR

CASSETTE BOARD CONNECTOR

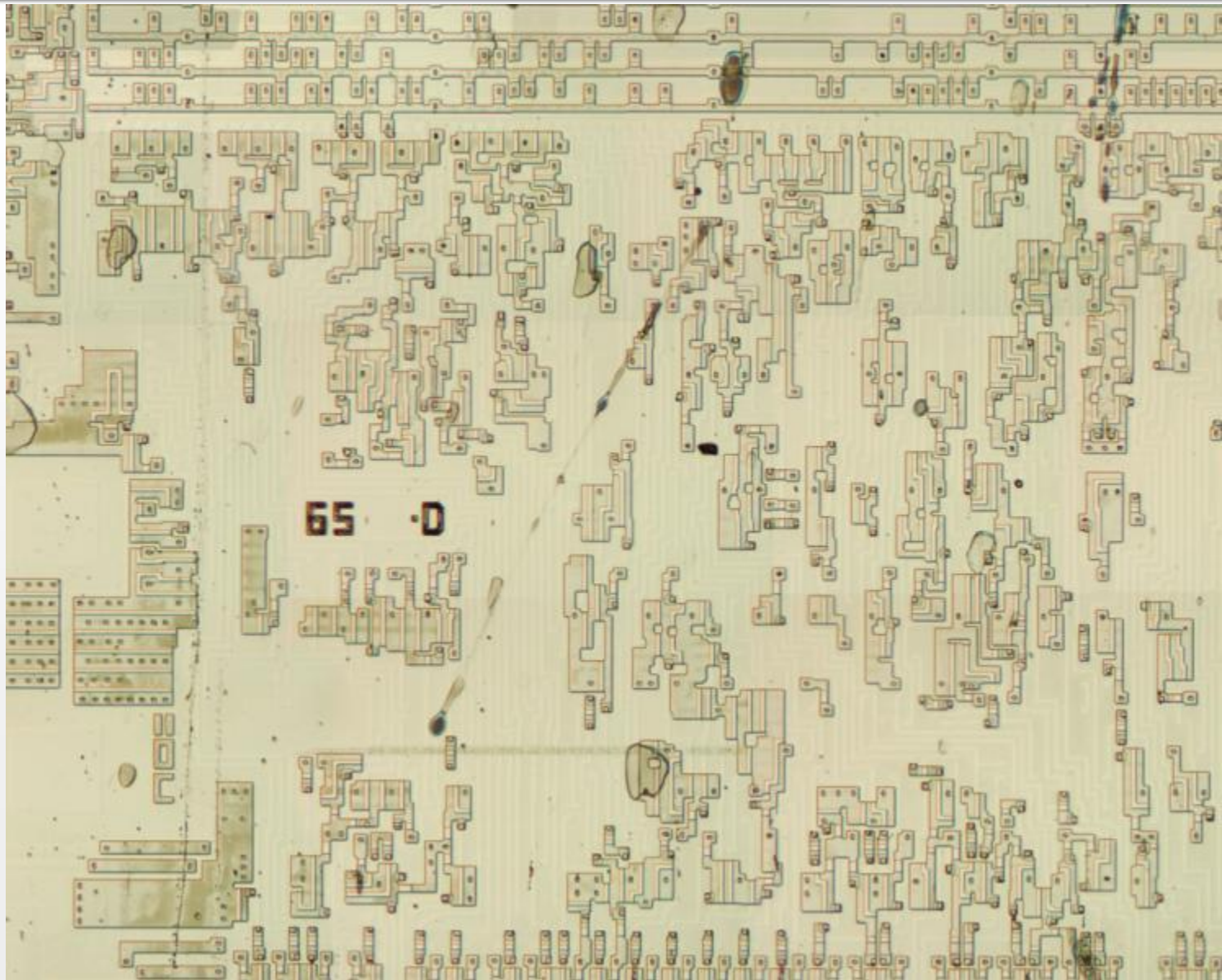
4 FULLY REGULATED POWER SUPPLIES

APPLE Computer Company • 770 Welch Rd., Palo Alto, CA 94304 • (415) 326-4248
JANUARY 1977 CIRCLE INQUIRY NO. 2 INTERFACE AGE 11

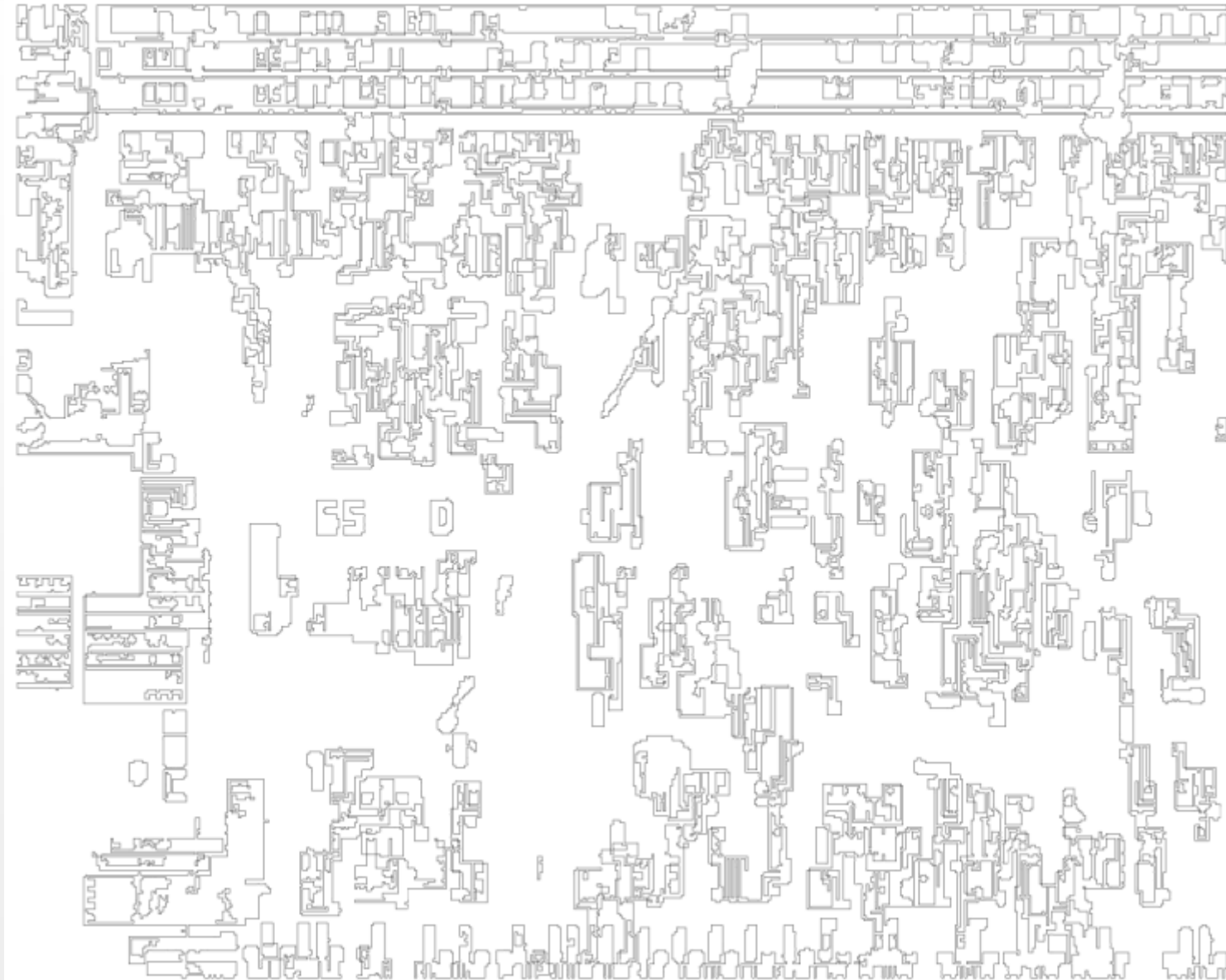
Apple I motherboard, 1977

Byte Magazine, 1977 [Klein] CCL 1.3

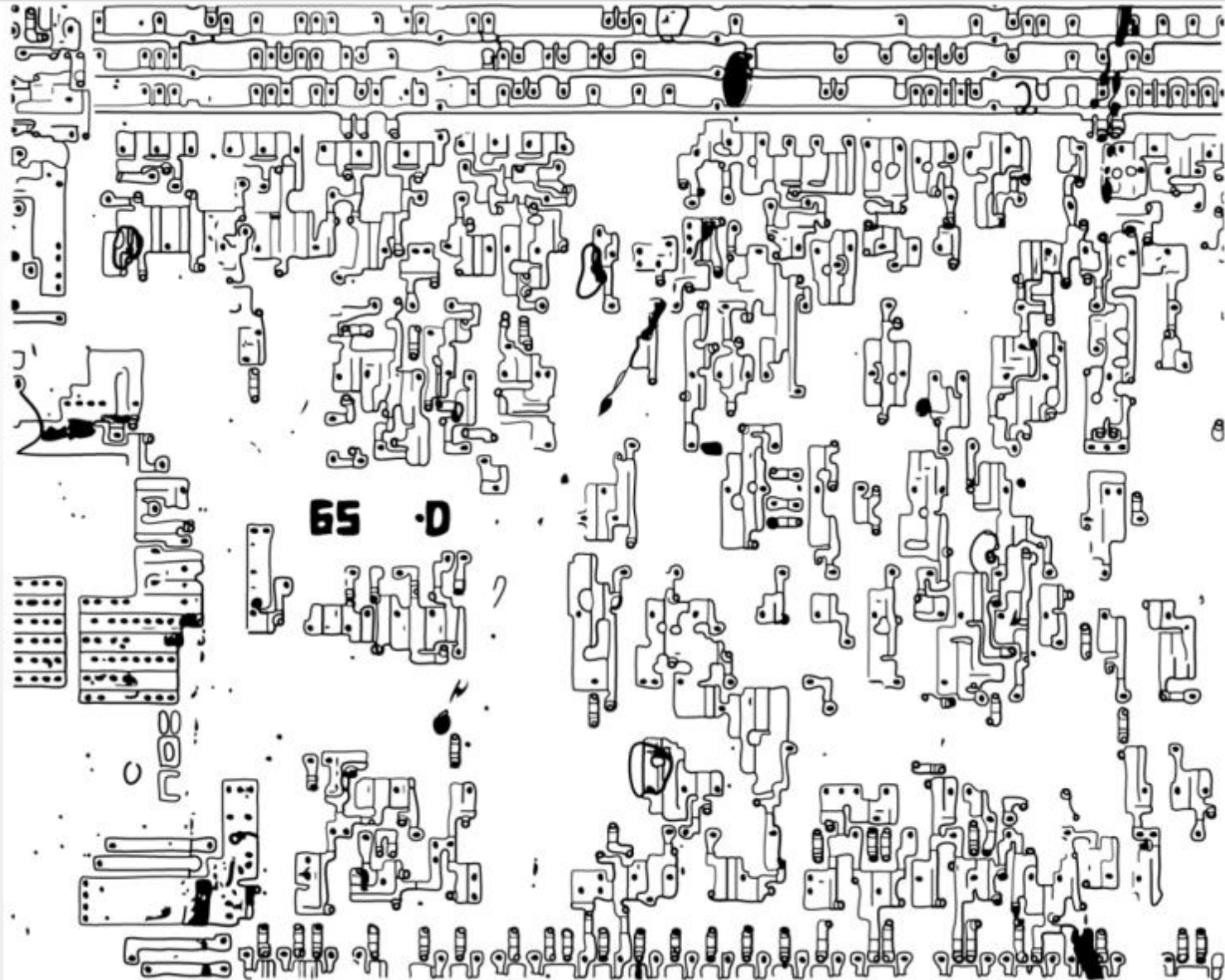
Automatic Vectorization - Input



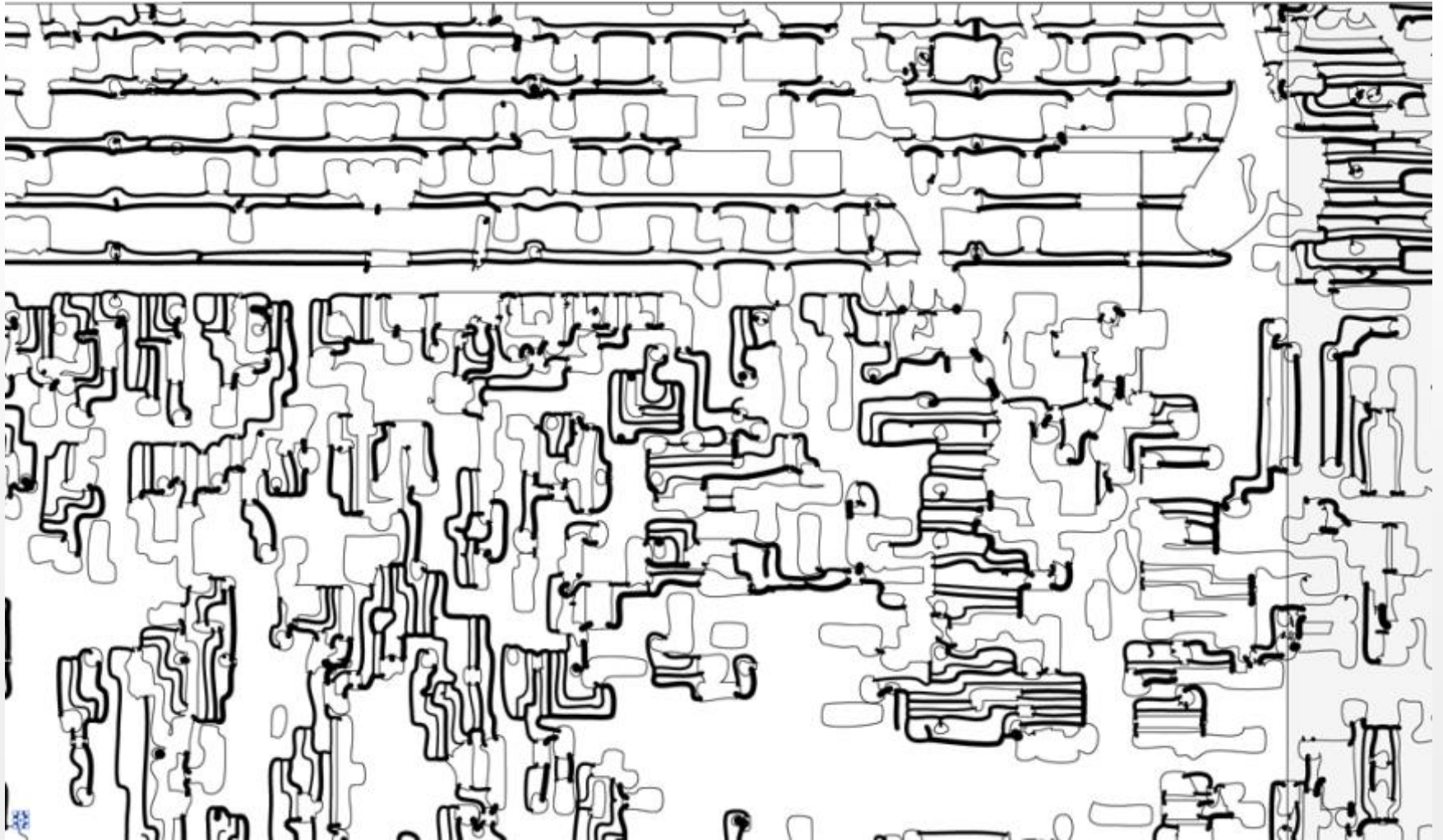
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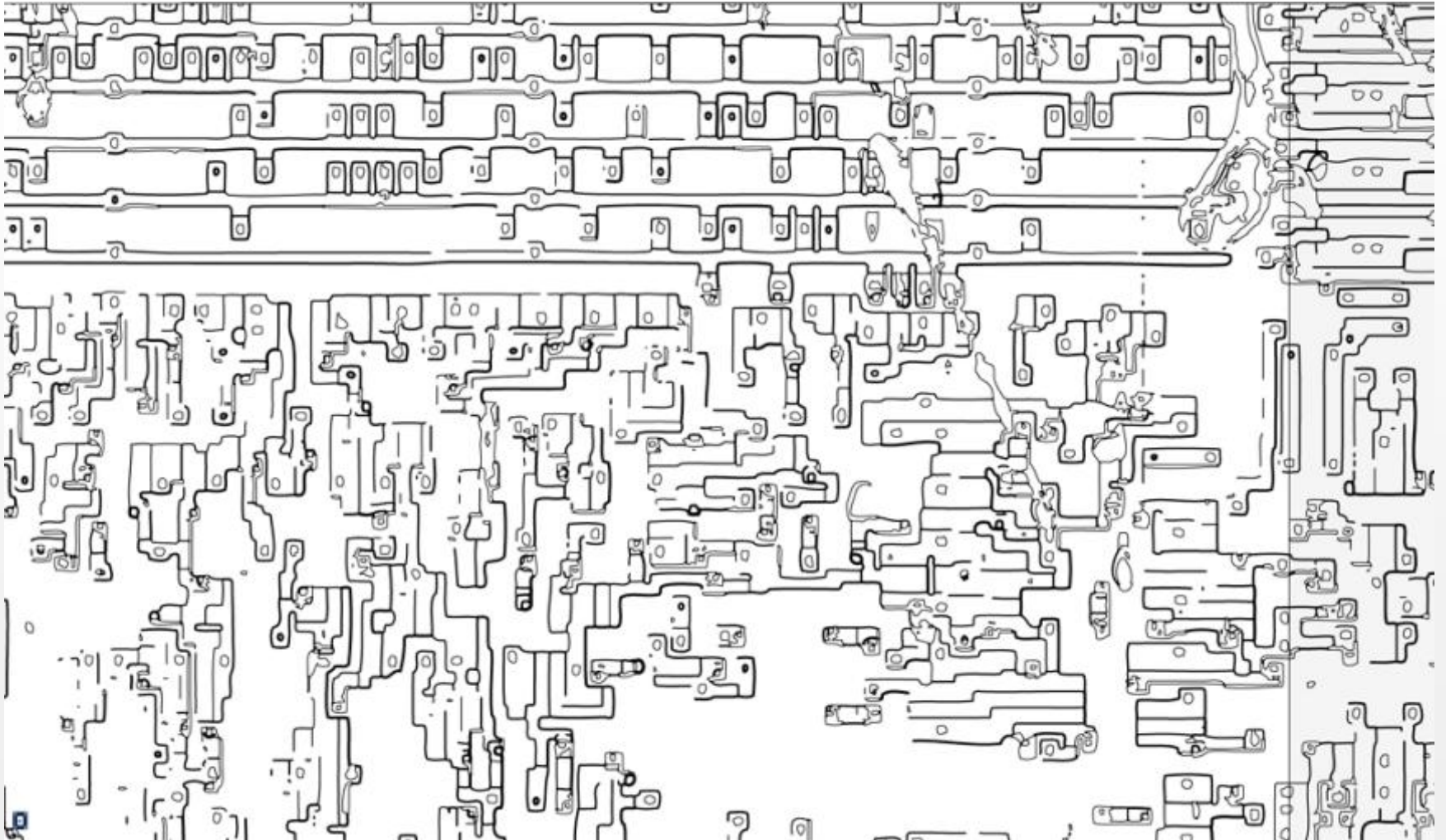
Automatic Vectorization – oops



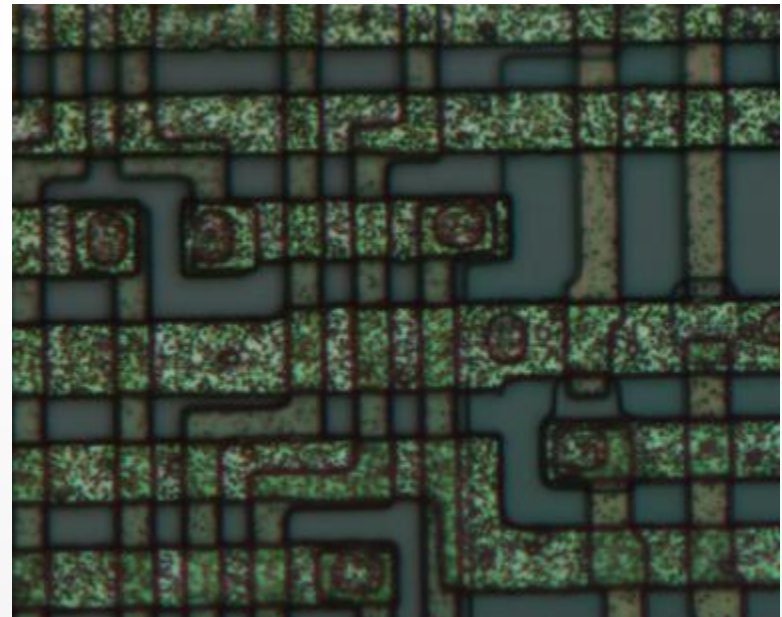
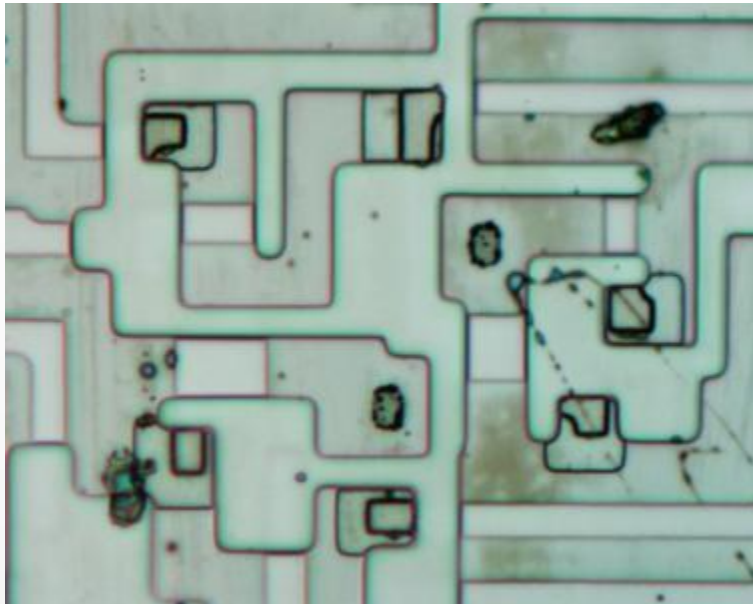
Automatic Vectorization – Hah!



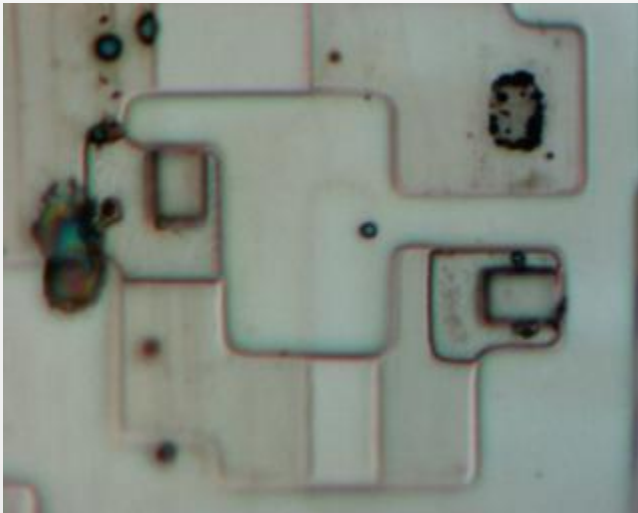
Automatic Vectorization



High Magnification Shots



50x
1800 shots to cover the chip :-)



100x
7200 shots to cover the chip x-)

MOS 6502 – Context



■ Released 1975

1961 – Steve Russel, MIT, first video game: Spacewars for PDP-1

1964 – First commercial graphics computer - IBM 2250 console, \$125,000

1969 – Intel 1 kb RAM chip. Bell Labs first framebuffer (3 bit)

1971 – Intel 4004

1972 – Atari founded, Pong. Xerox PARC 8-bit framebuffer.

Intel 8008 8-bit processor

1973 – Triple I + Evans & Sutherland market first commercial framebuffer. Ethernet. Moore's Law

1974 – Ed Catmull, Utah: Z-Buffer and texture mapping

Computer Graphics Lab at NYIT opens

Intel 8080 - 2 mHz, 10x faster than 8008, \$150

1975 – Frank Crow: antialiasing

Motorola 6800 selling for \$175.

Wozniak discovers MOS 6502, selling for \$25, finished Apple I by 1976

1977 – Apple incorporated. Apple II released in April

TRS-80

1978 – DEC VAX 11/780 @ 5 mhz. 16 kb RAM chip \$500. Commodore PET \$595. TRS-80 for \$600

1979 – Atari 400/800 8-bit computers. Motorola 68000 processor. IBM 3279 color terminal

1982 – Atari hits \$2 billion in revenue, making it the fastest growing company in history

Source: http://sophia.javeriana.edu.co/~ochavarr/computer_graphics_history/historia