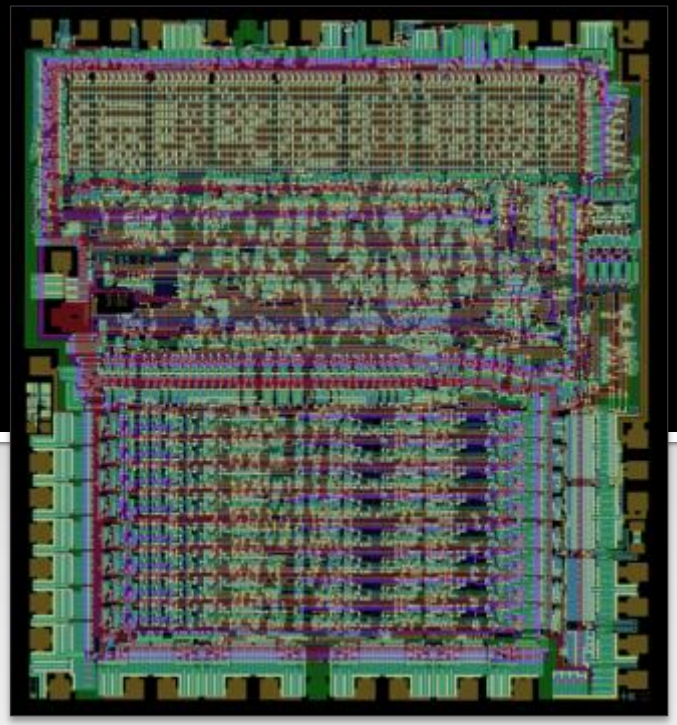
Visualizing a Classic CPU In Action: The 6502

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.

Introduction

MOS Technology's

6502 CPU

Released 1975

Apple I, II

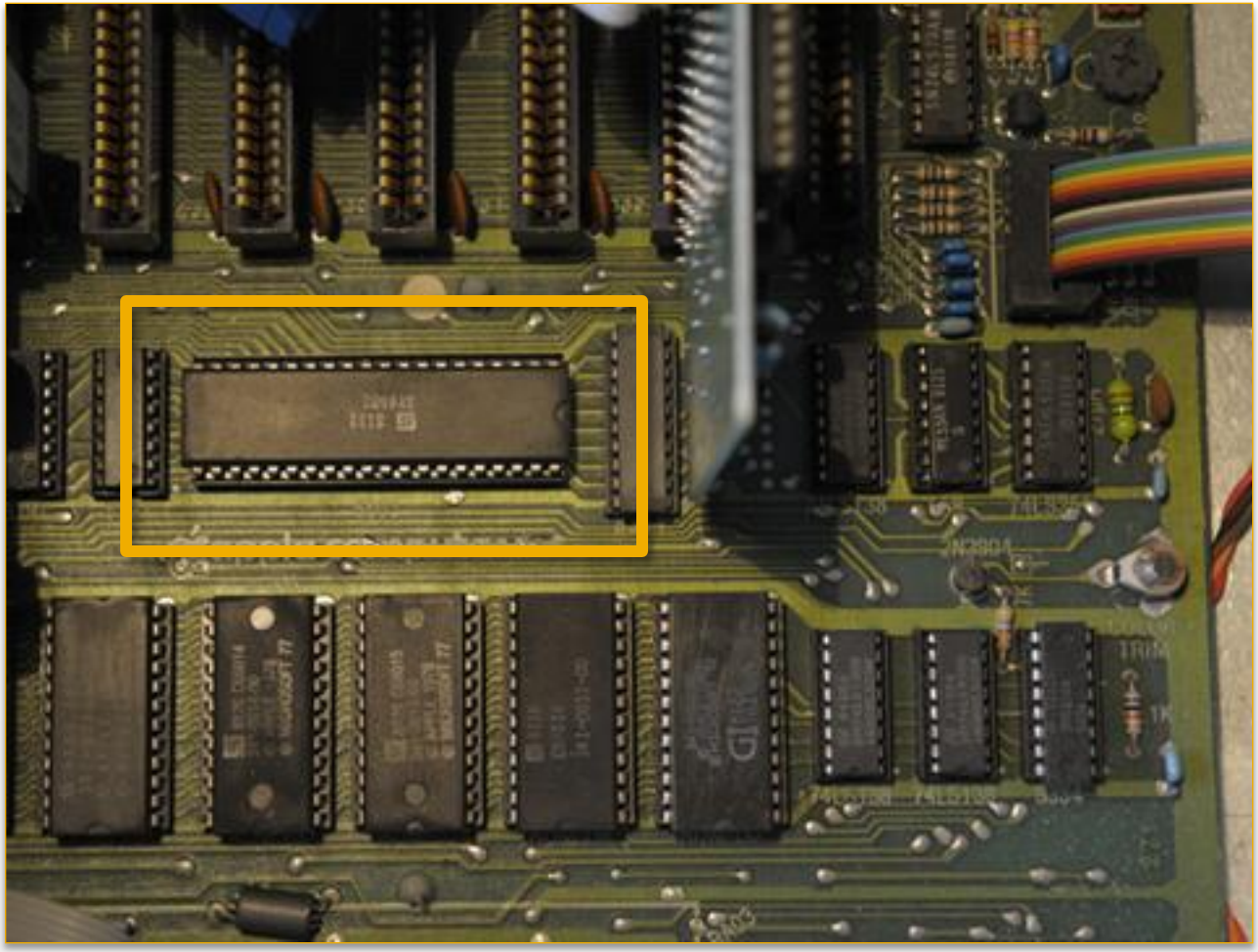
Commodore PET, C64

Atari 2600 (6507)

Atari 400, 800

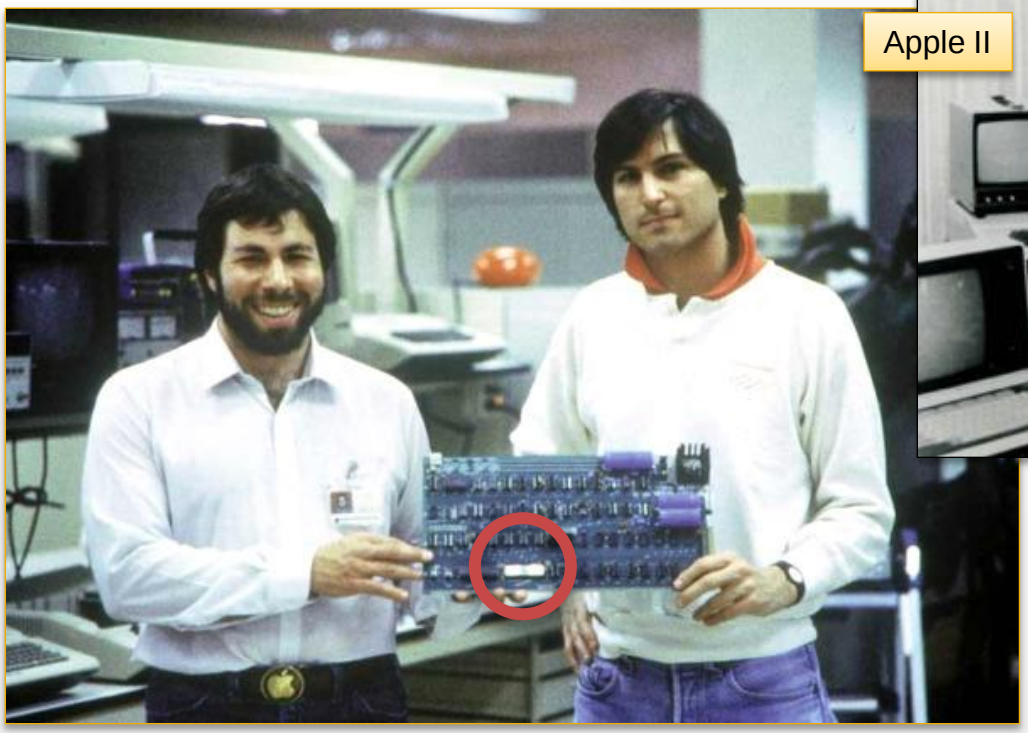
Nintendo NES

Apple II Plus motherboard



6502 – Everywhere

Steve Wozniak, Steve Jobs



Apple I

[Klein] CCL 1.3

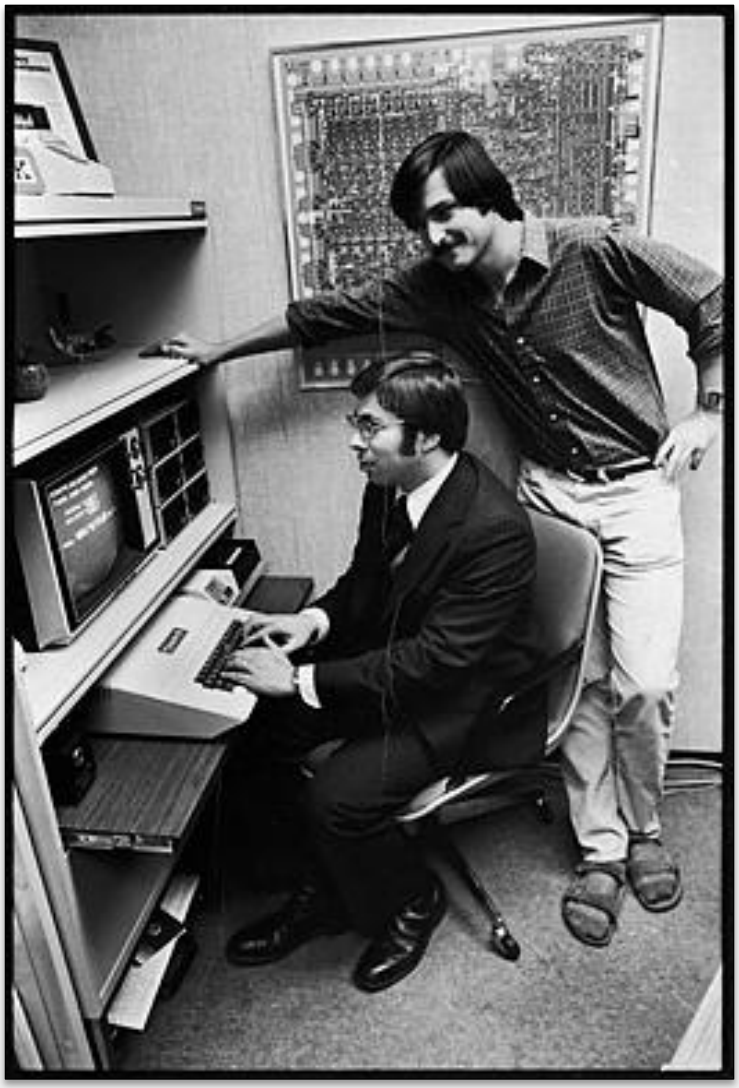
Paul Allen, Bill Gates

Apple II

[Klein] CCL 1.3

Commodore PET

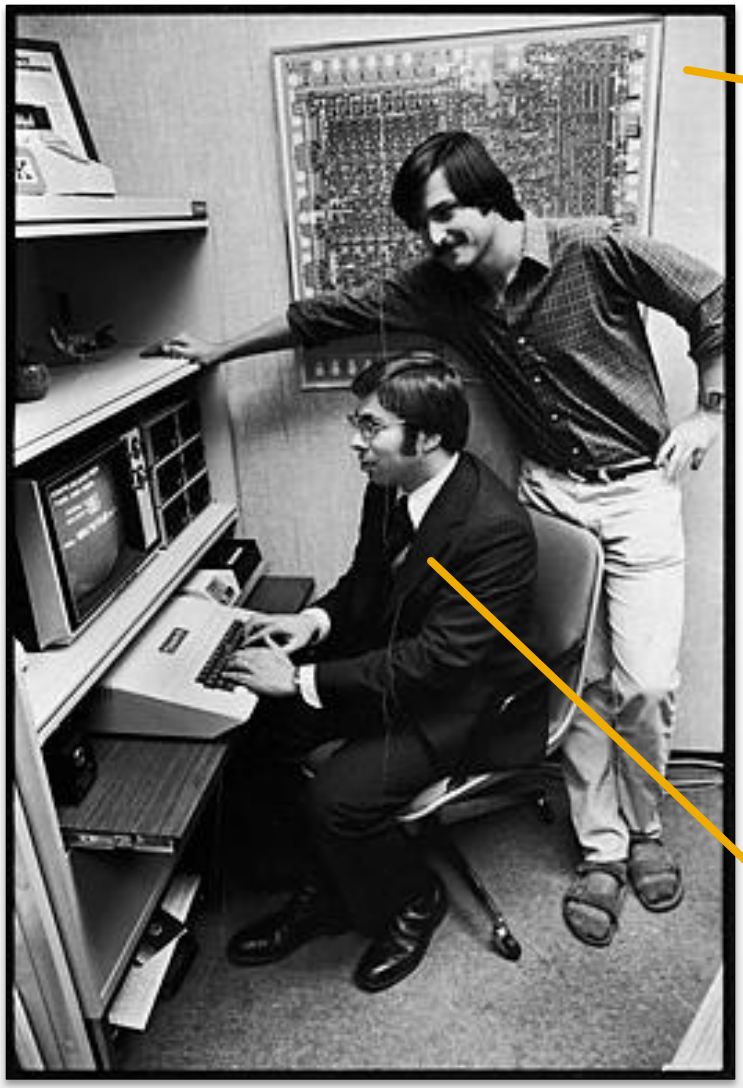
Wall Art?



[Klein] CCL 1.3

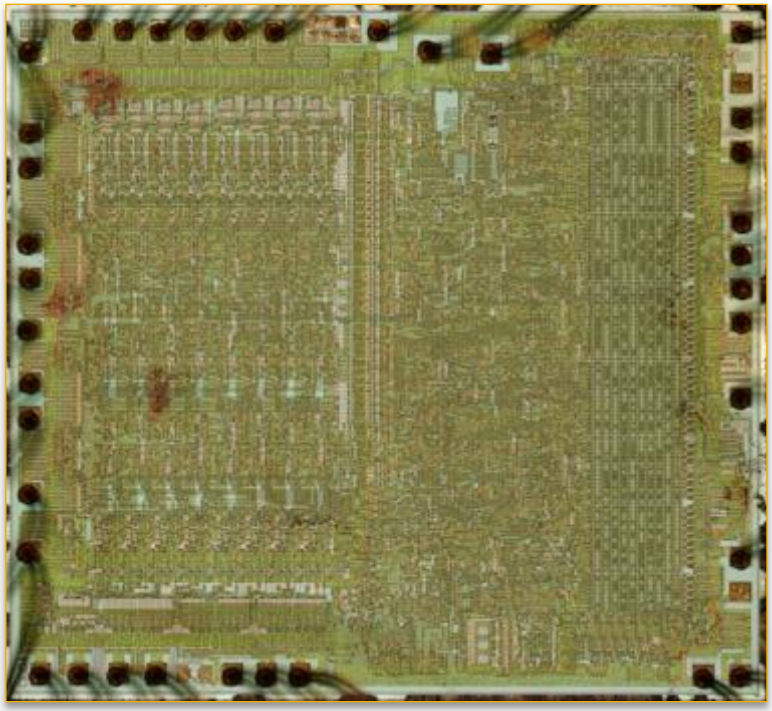
Jobs, Wozniak, and …

Wall Art: 6502 die shot



[Klein] CCL 1.3

Jobs, Wozniak, and …



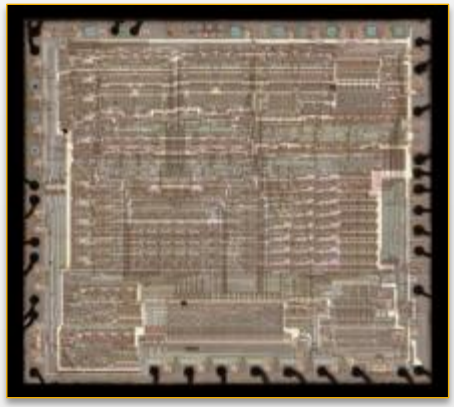
The 6502

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.

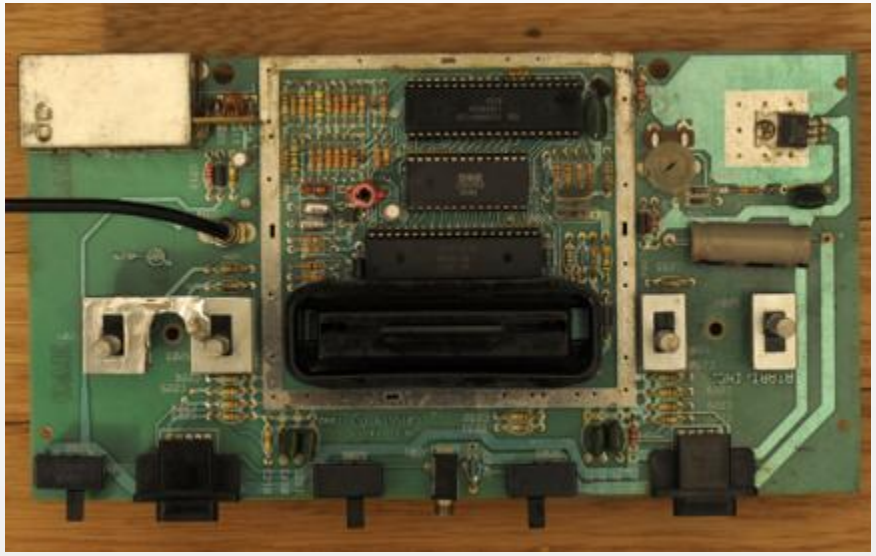
Introduction

- 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+

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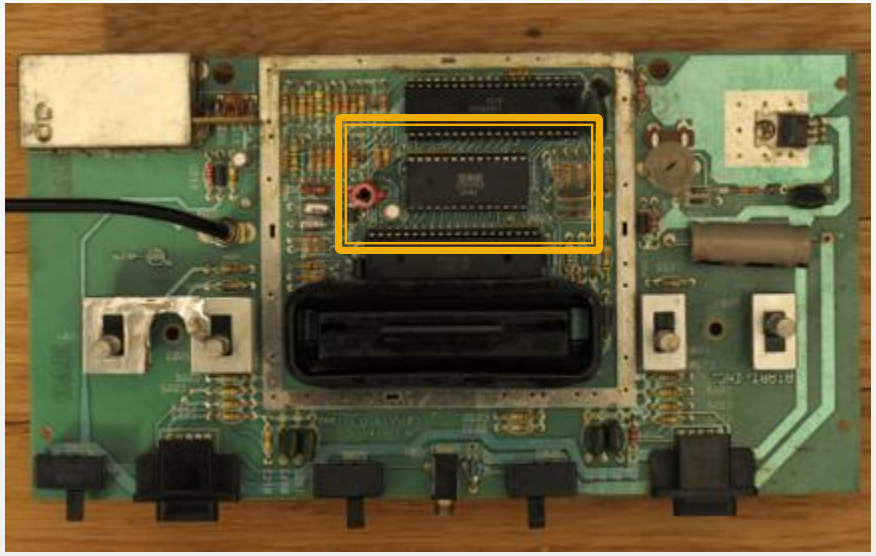
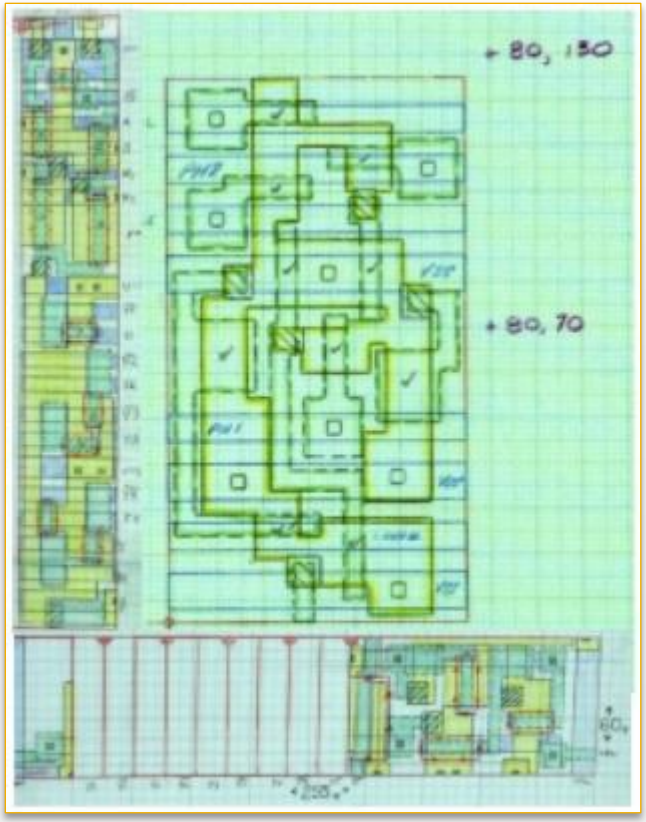


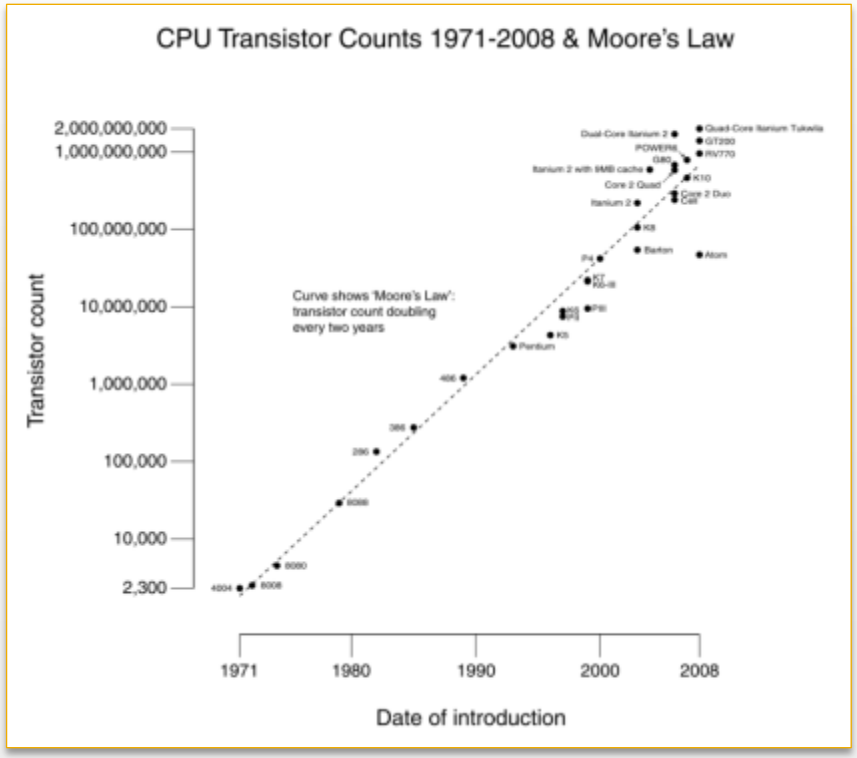
  - Apple II+

6502, lost design

- Before ~1980, chip design was a very manual process



[Volk'01] Used with permission



Wikimedia Commons, GFDL

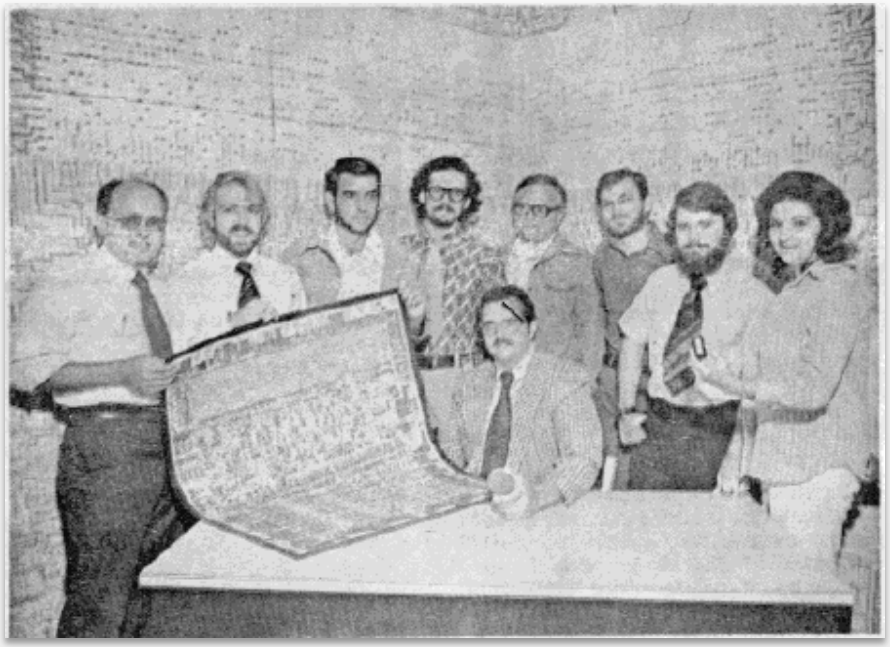
Chip Design by Hand, c.1976

- 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



EE Times, Aug 25, 1975, courtesy of W. Mensch

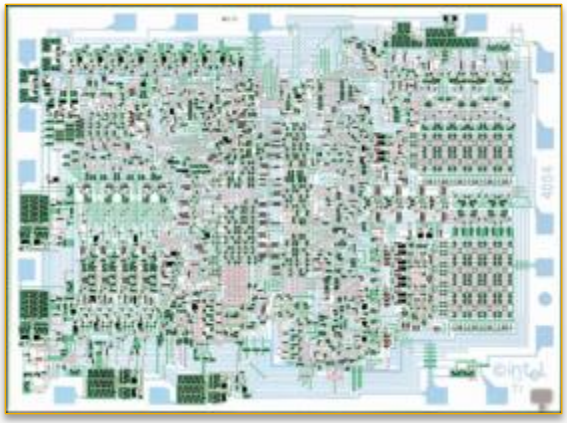
MOS designers with Rubylith 6502
L to R:
Layout Designers:
Sydney-Anne Holt, Michael Jaynes, Harry Bawcom.

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

Seated, Product Manager: Terry Holdt

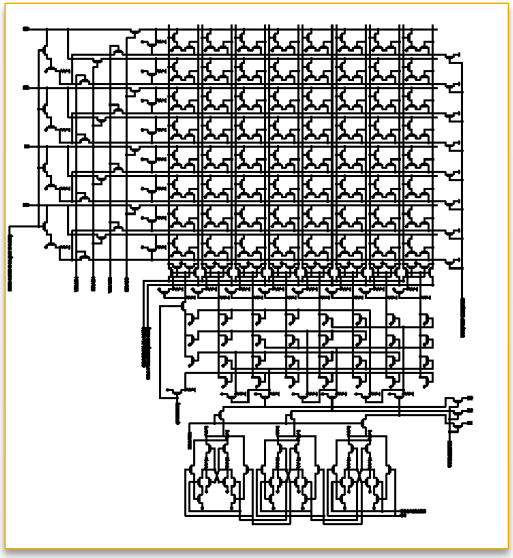
Prior Work

- 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

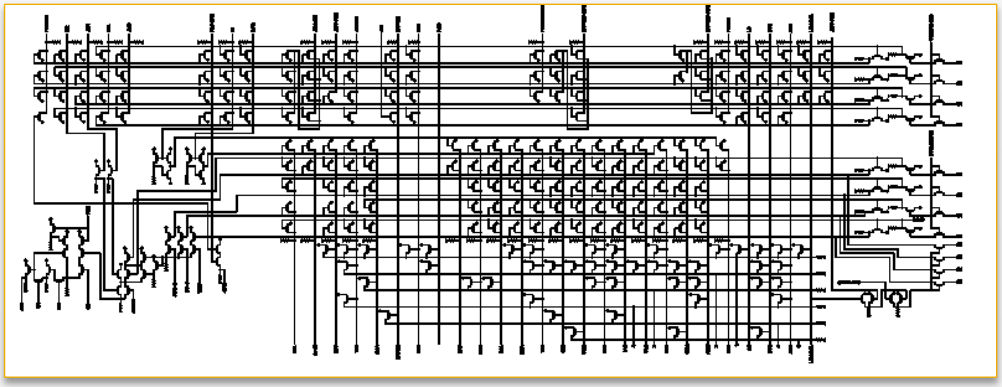


Intel 4004 Project, CCL1.3

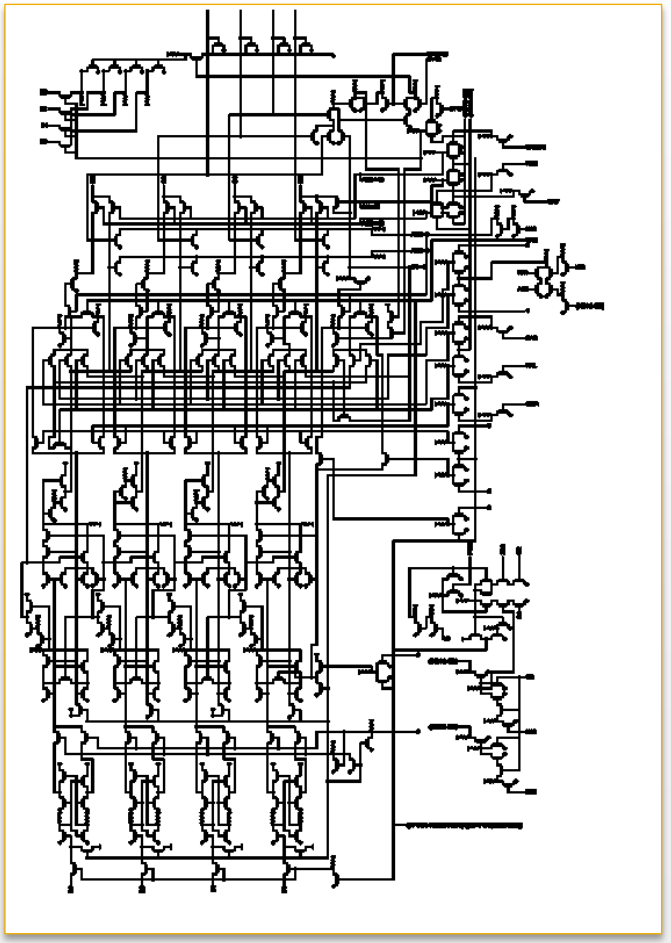
Intel 4004 Project



Registers

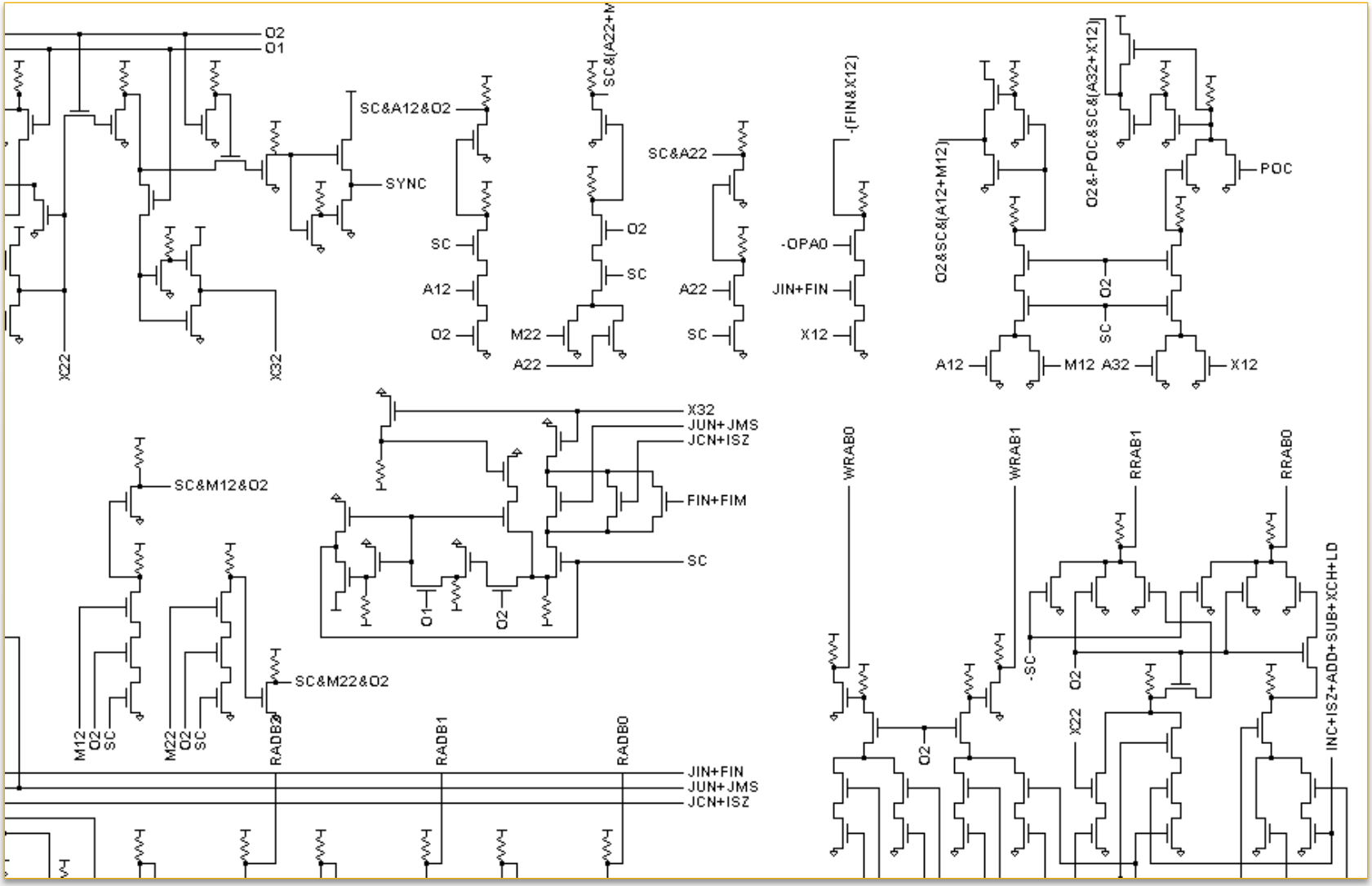


Instruction Decode



ALU

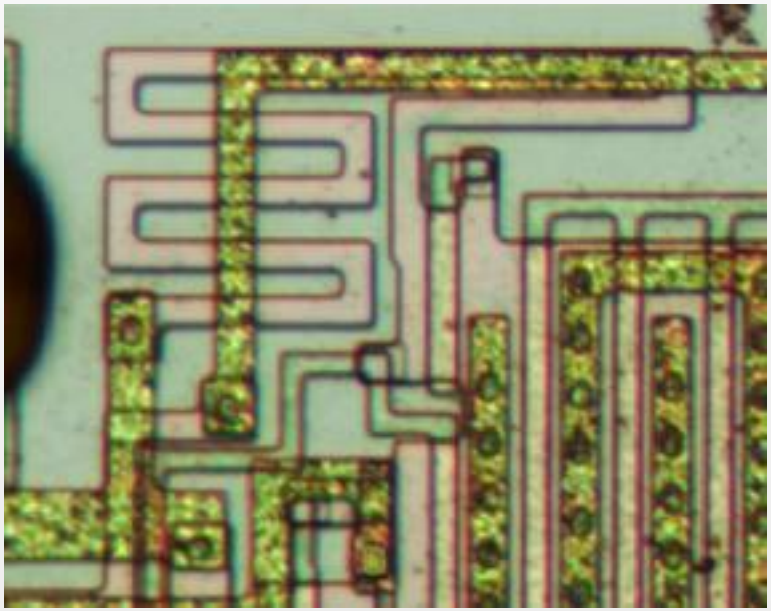
Intel 4004 Project

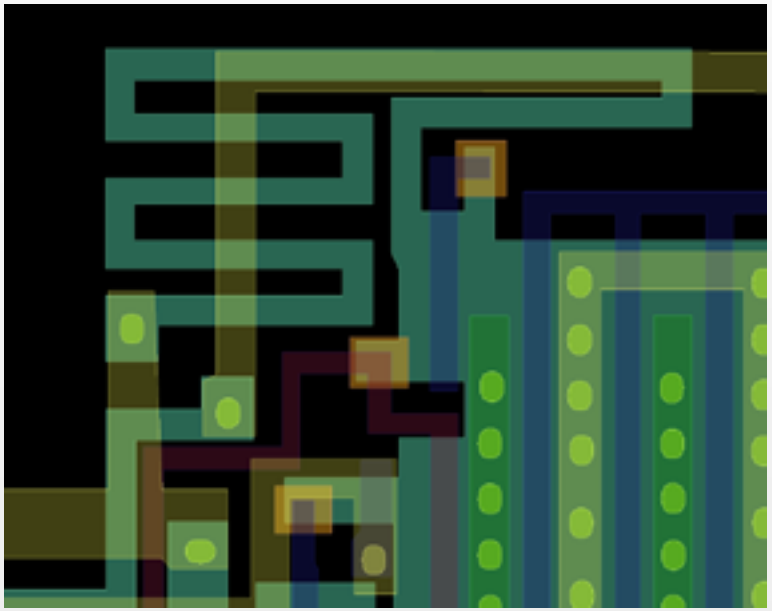


Brian Silverman, Barry Silverman, CCL 1.2

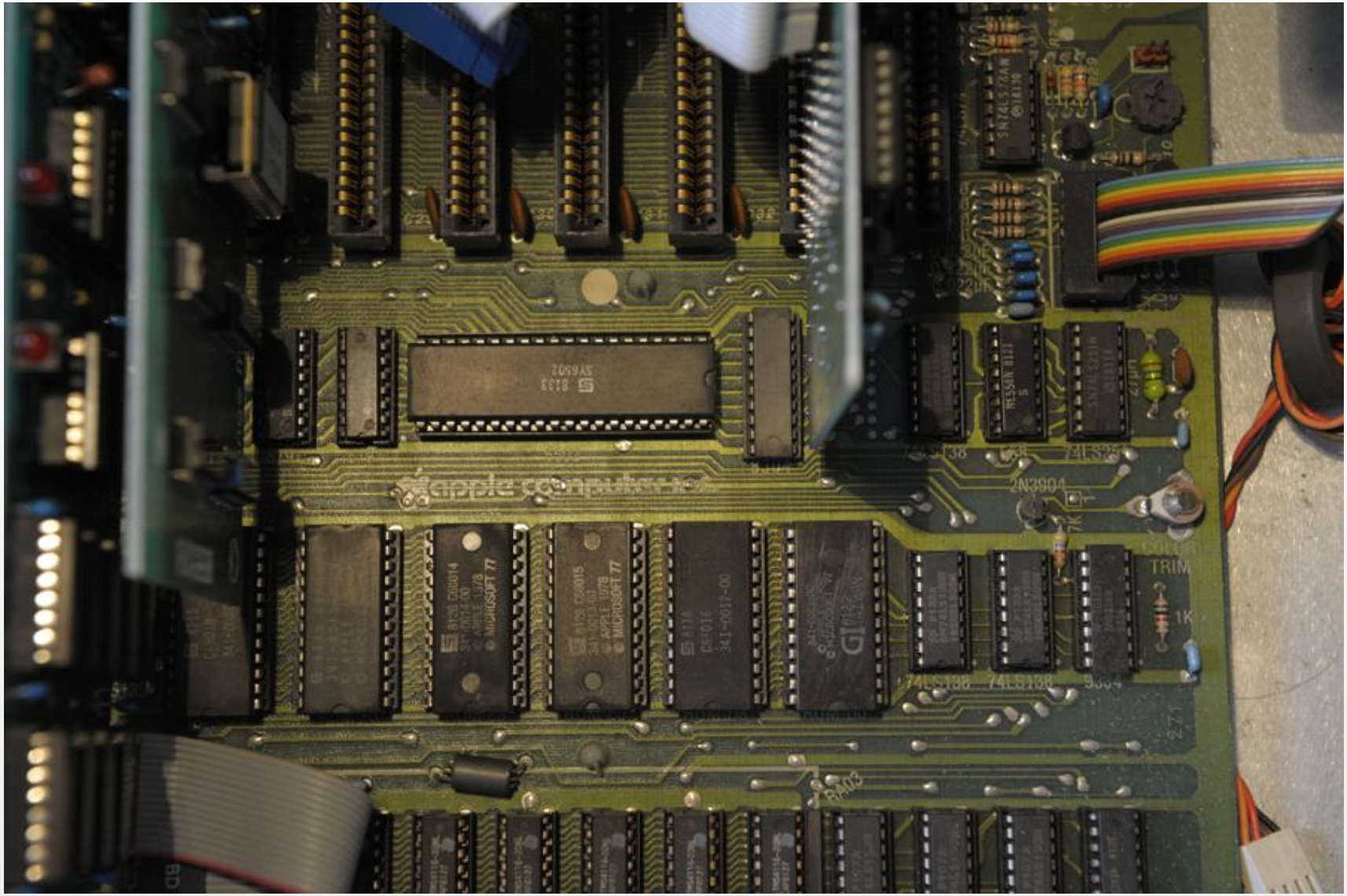
Our Approach

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

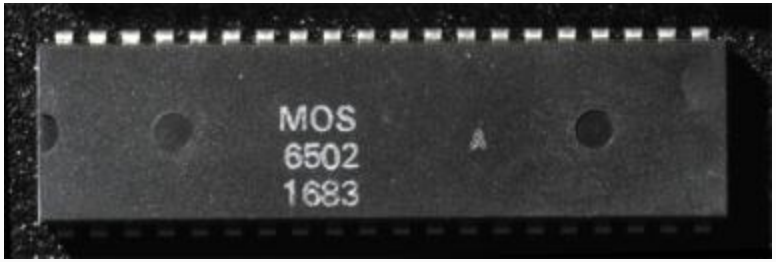


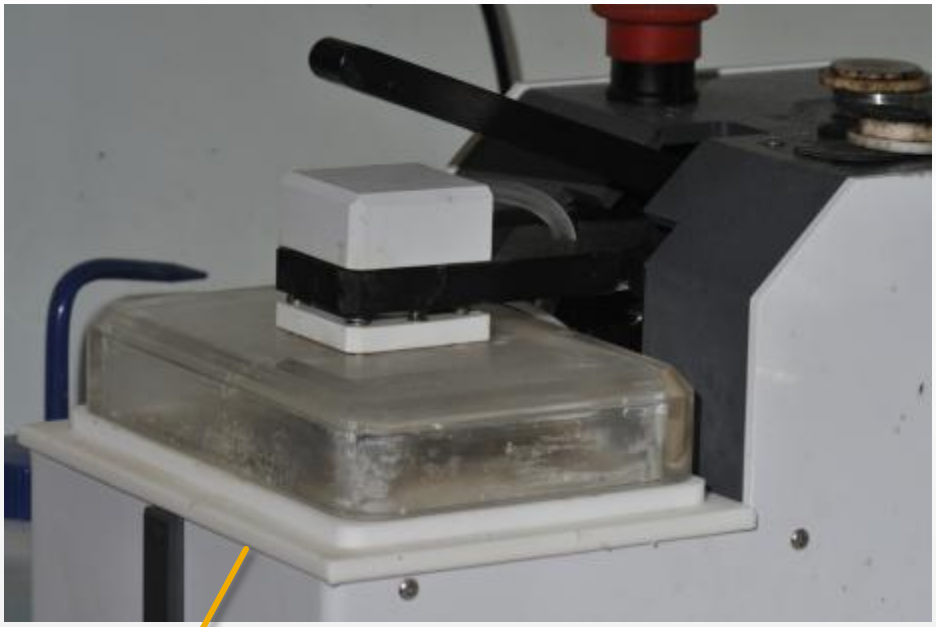


Apple II+

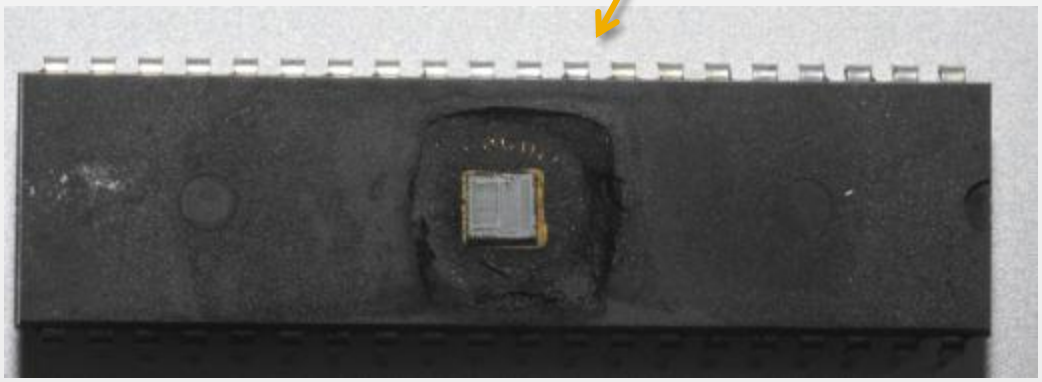

apple computer inc
MICROSOFT '77
APPLE '77B
341-0011-00
74LS138
74LS32
2N3904
TRIM
1K
7K

De-capping / de-packaging

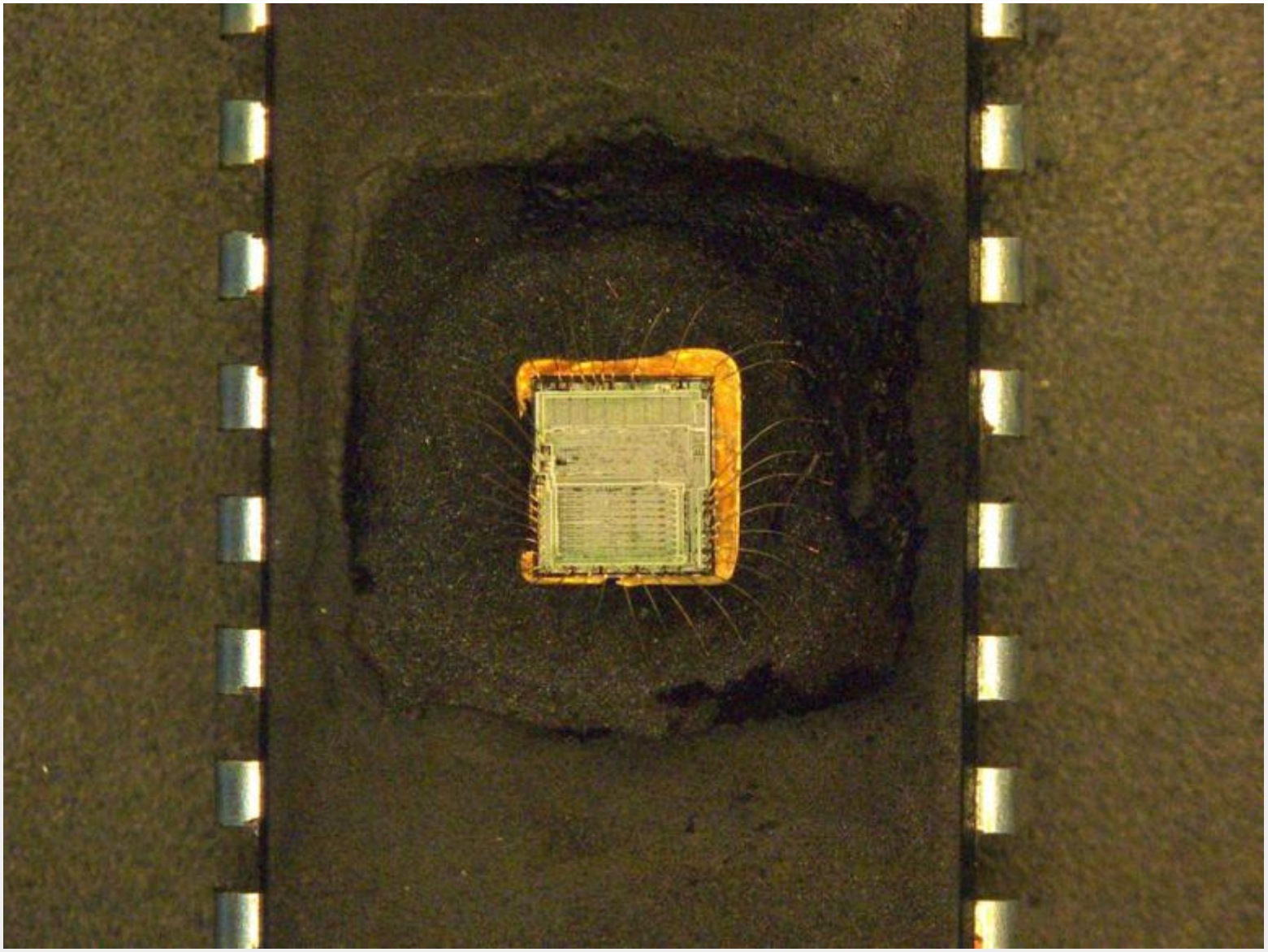




Squirts hot sulfuric acid (200º F)

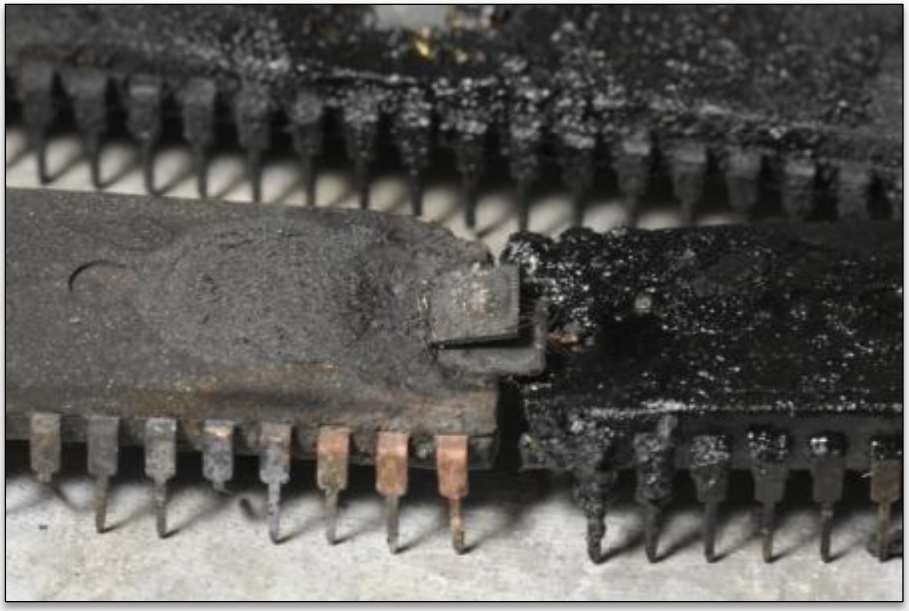


De-capped 6502



Sometimes, not so pretty

These are still ok
after we clean them up!

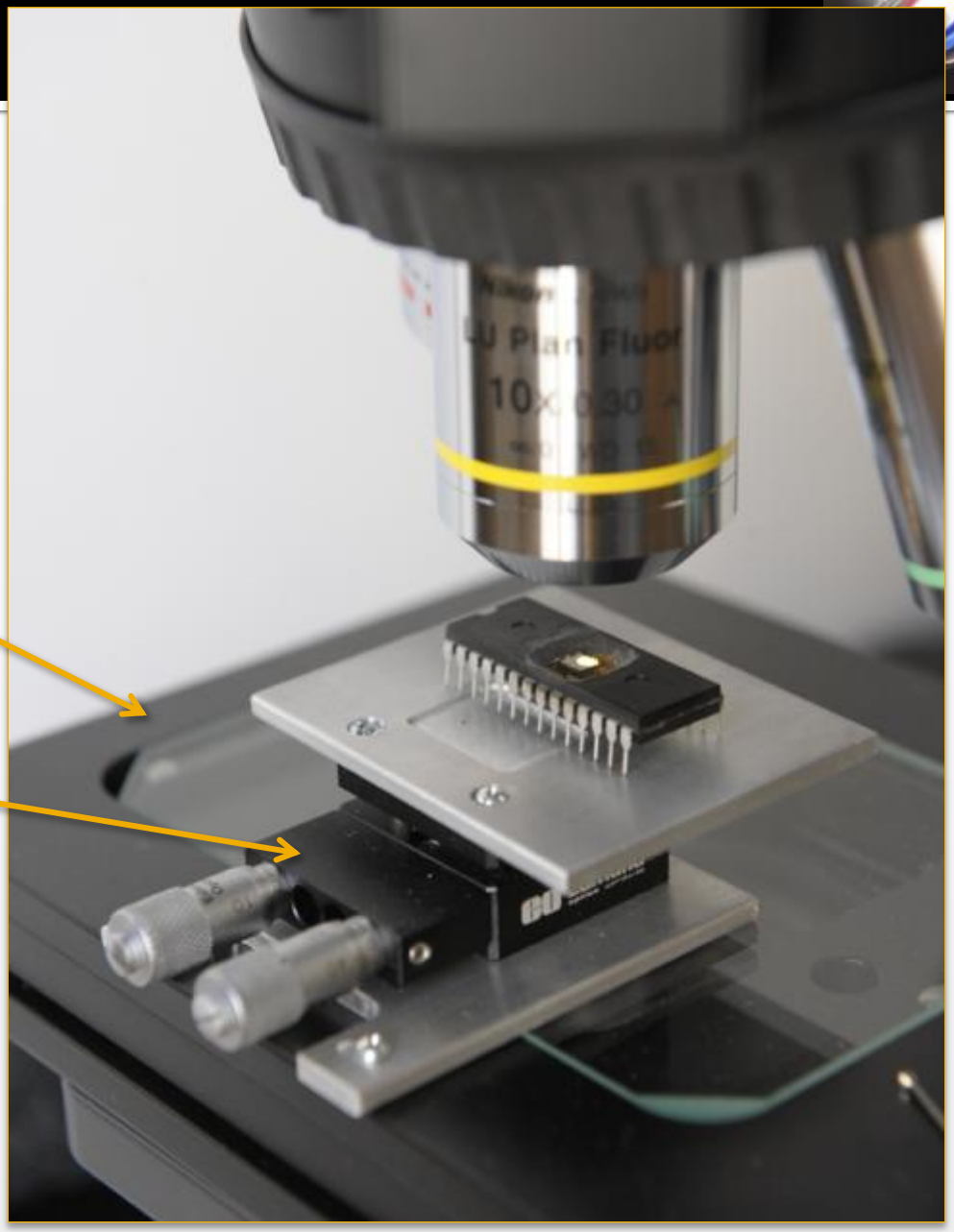


Microscopes

- Nikon Optiphot 200
- Nikon LV150
- 5x**, 10x**, 20x objectives

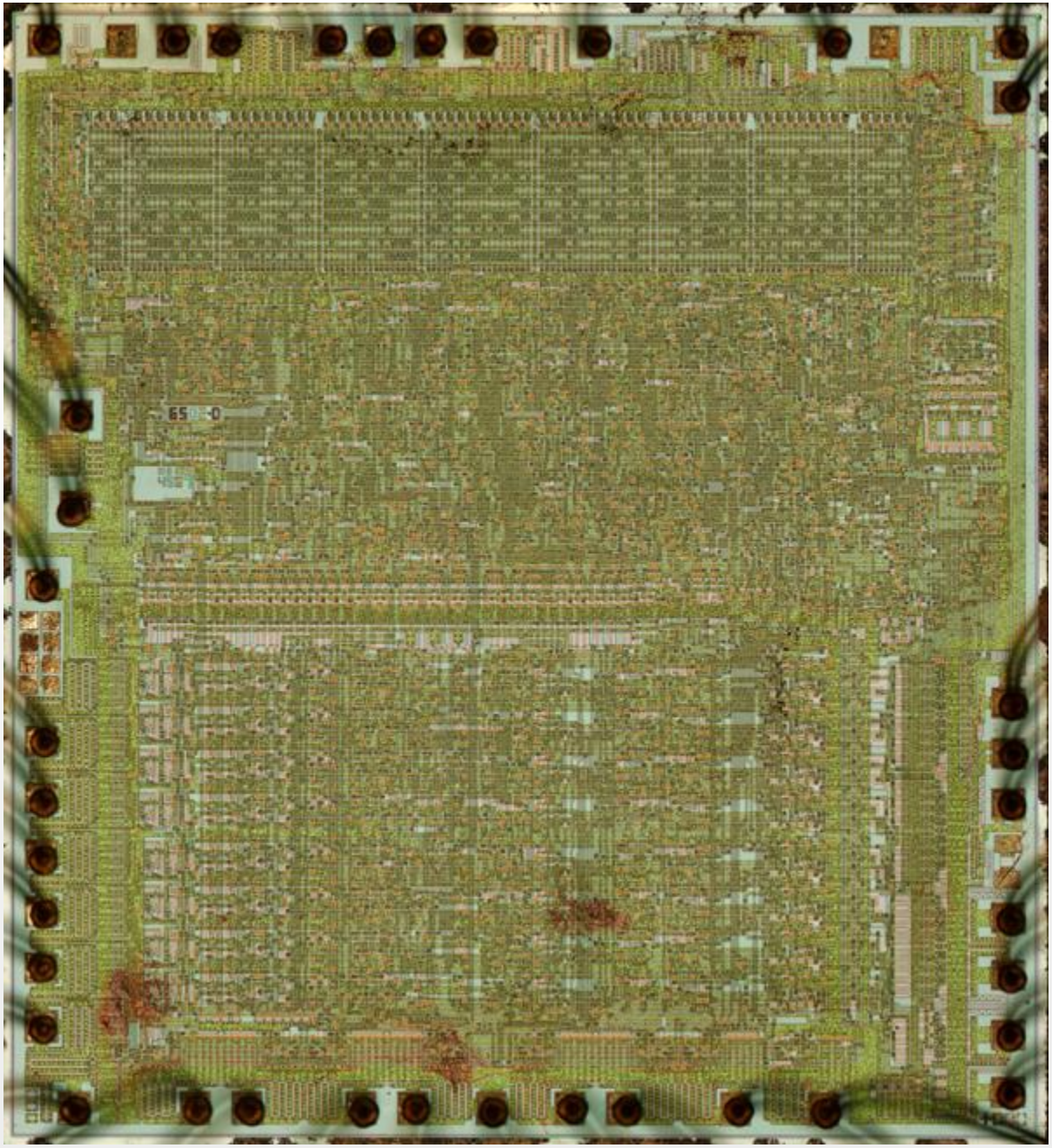
- X-Y translation stage to stitch many shots

- 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

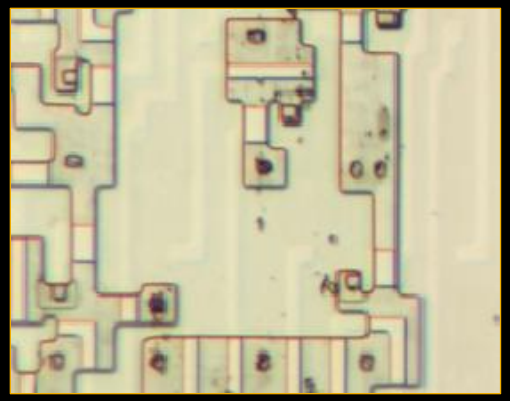
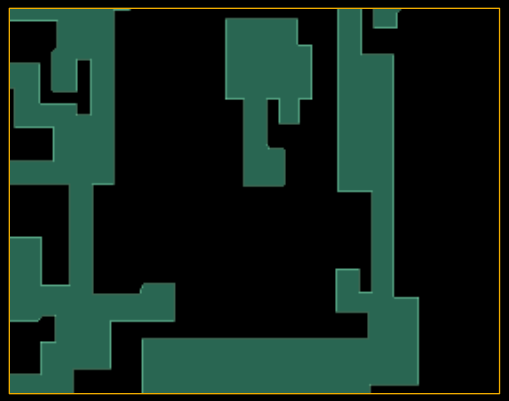
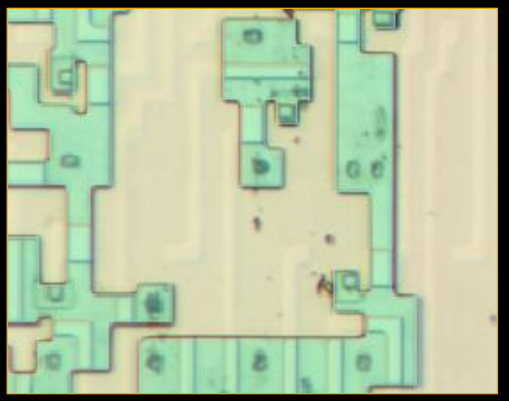
Only need ~6000 x 5800
for what comes next…

Chip Browser

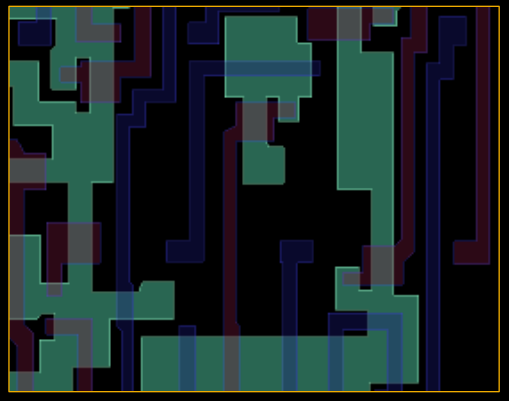
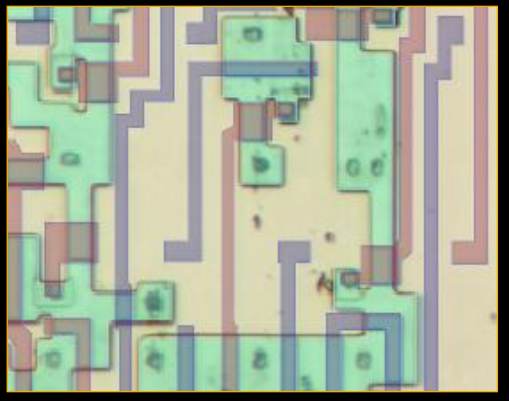
- Demo

Chip Layers

- Conductive Substrate

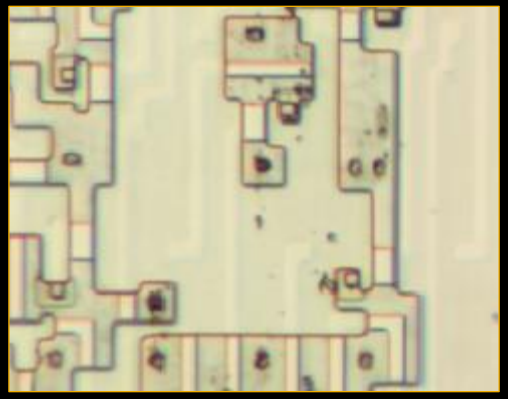
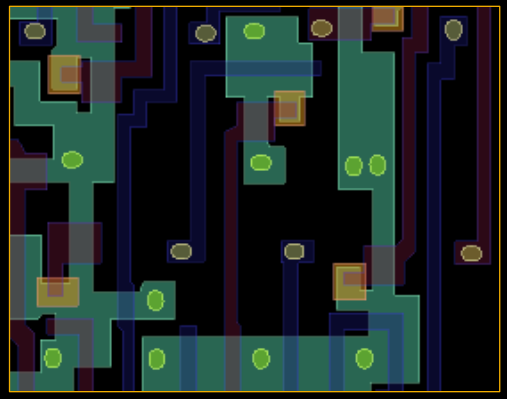
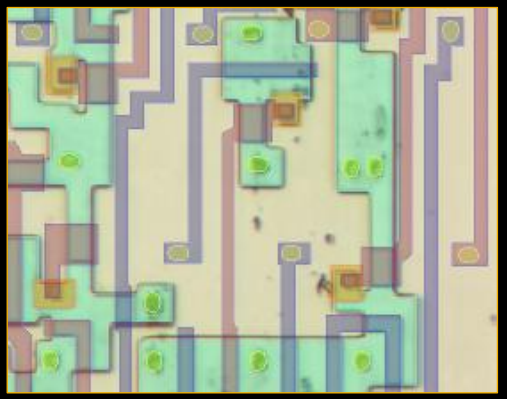




- Transistor-forming wires (polysilicon)

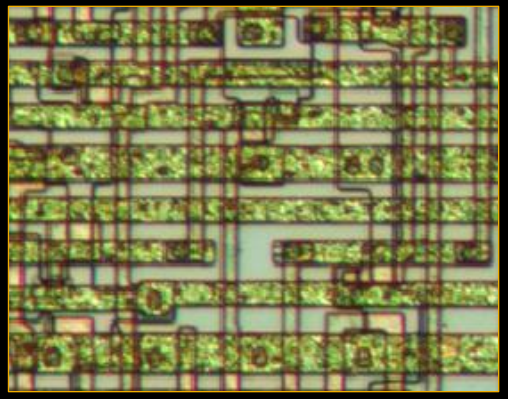
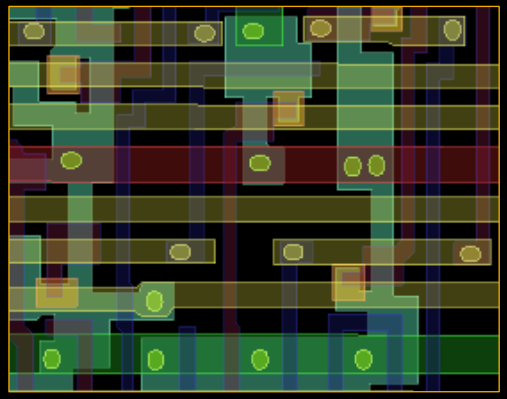
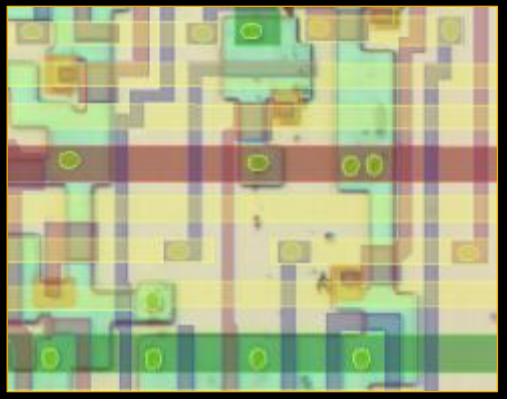



Chip Layers

- Vias and buried contacts

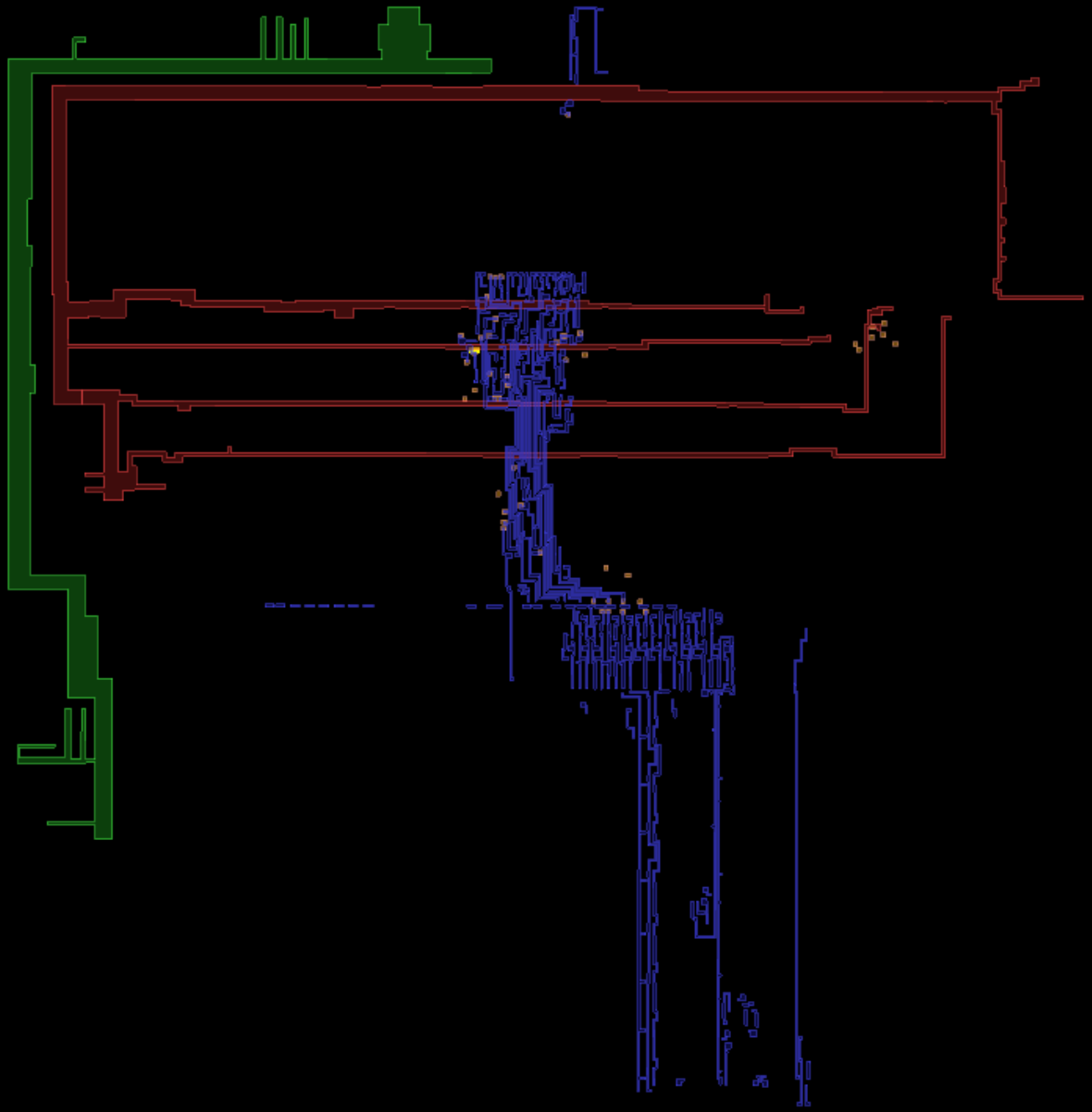




- Metal Interconnects

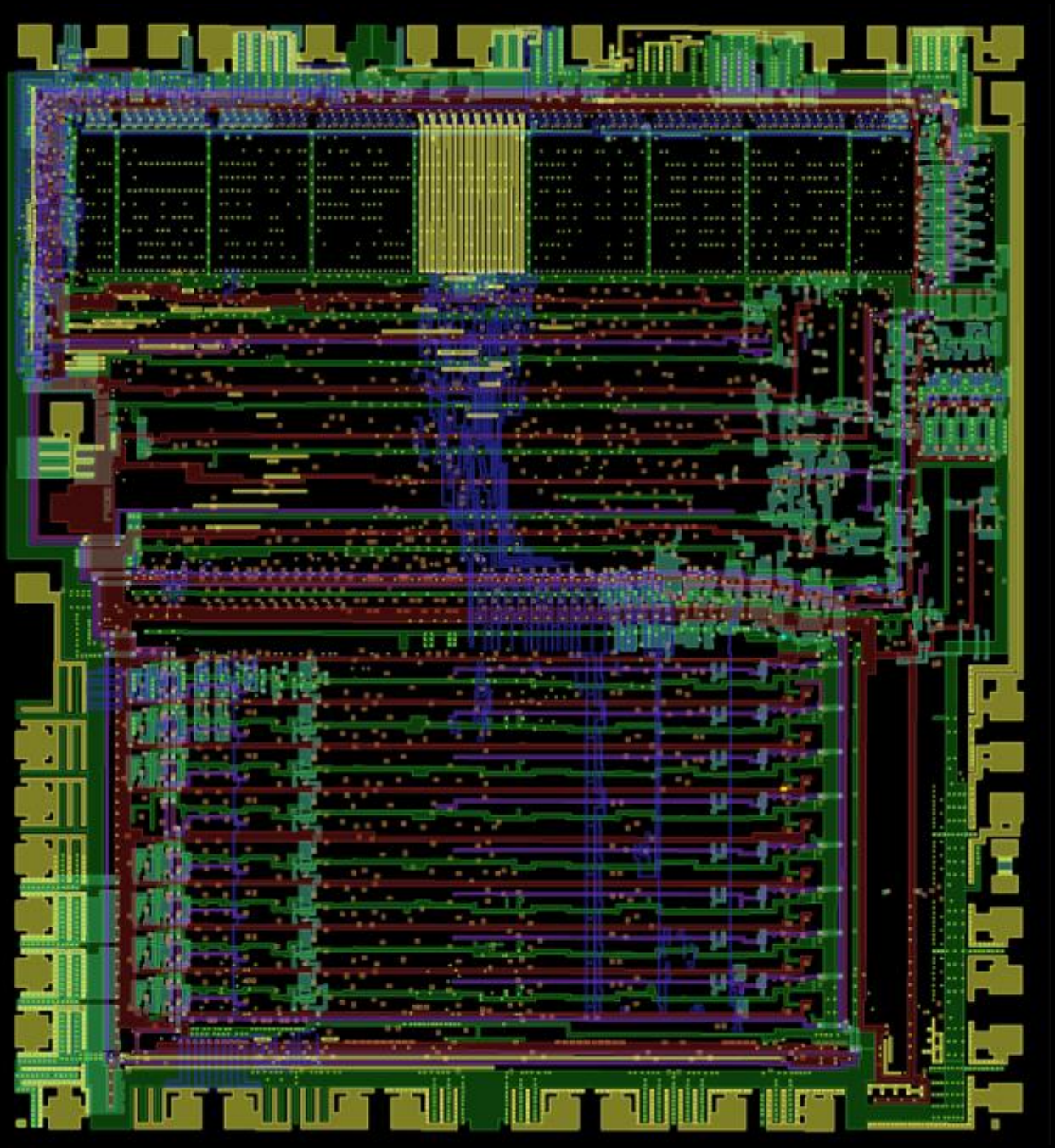
From Polygons to Simulation

- Demo

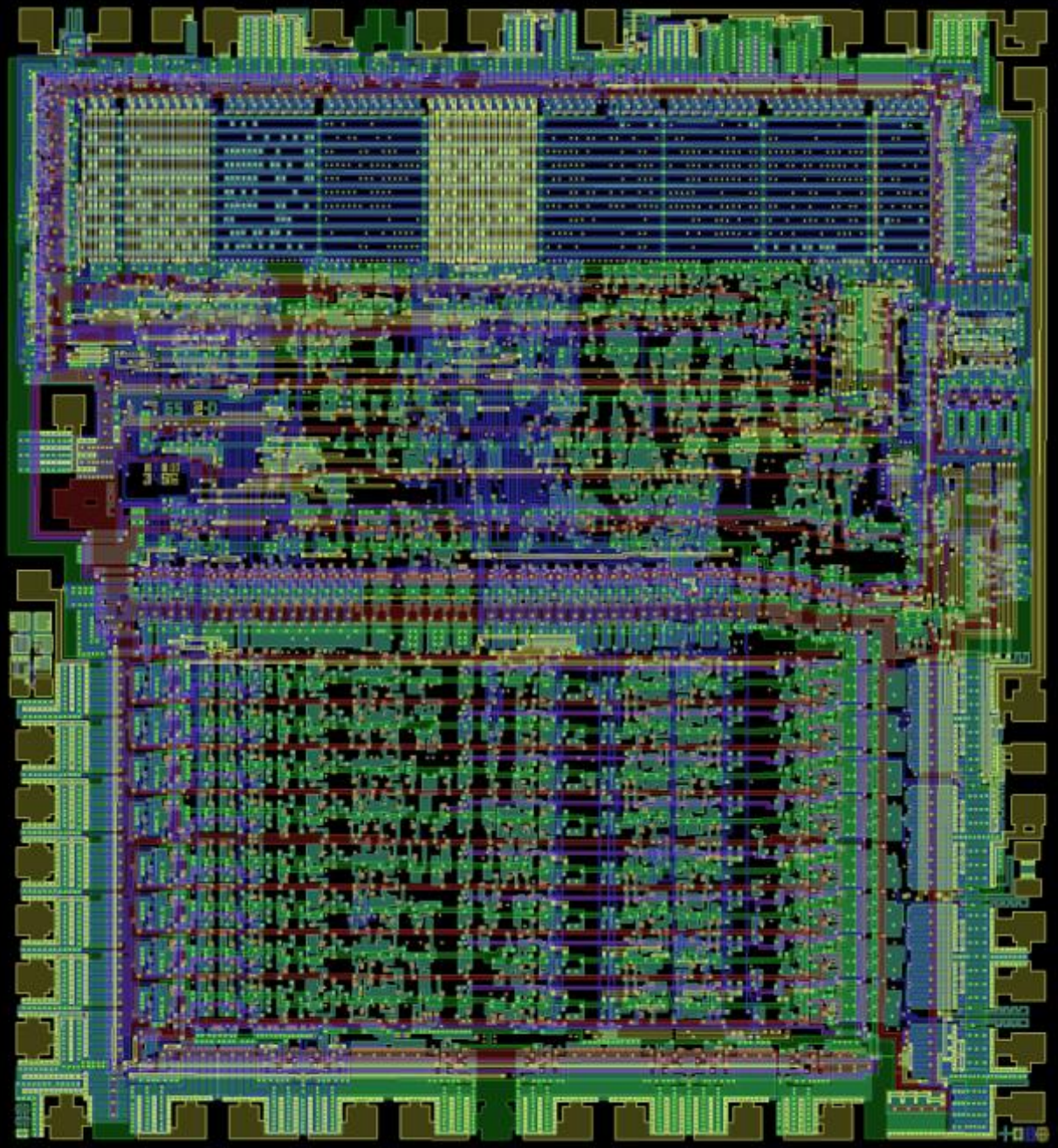


Polygon model began Nov. 11, 2009

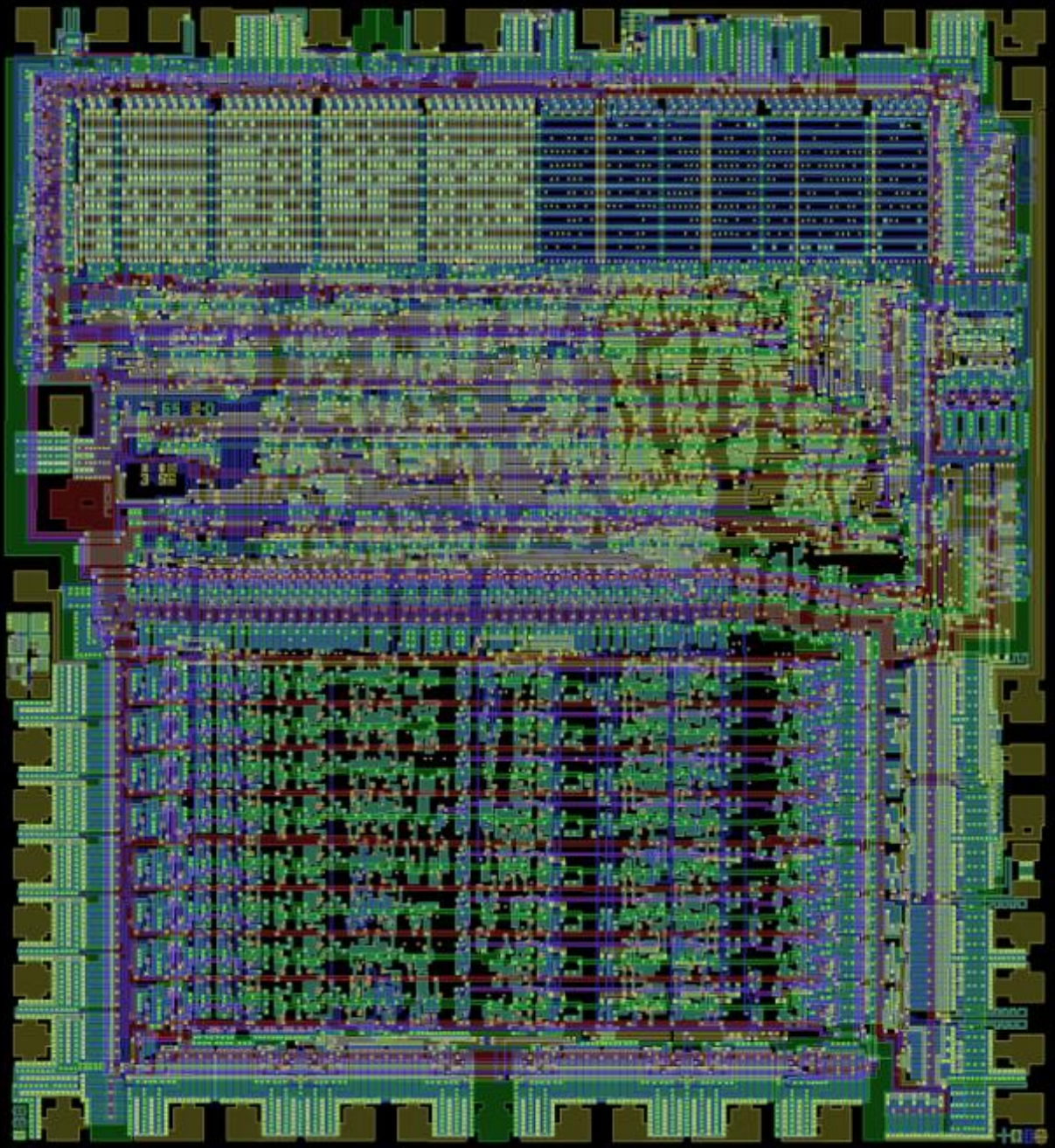
Nov. 16, 2009



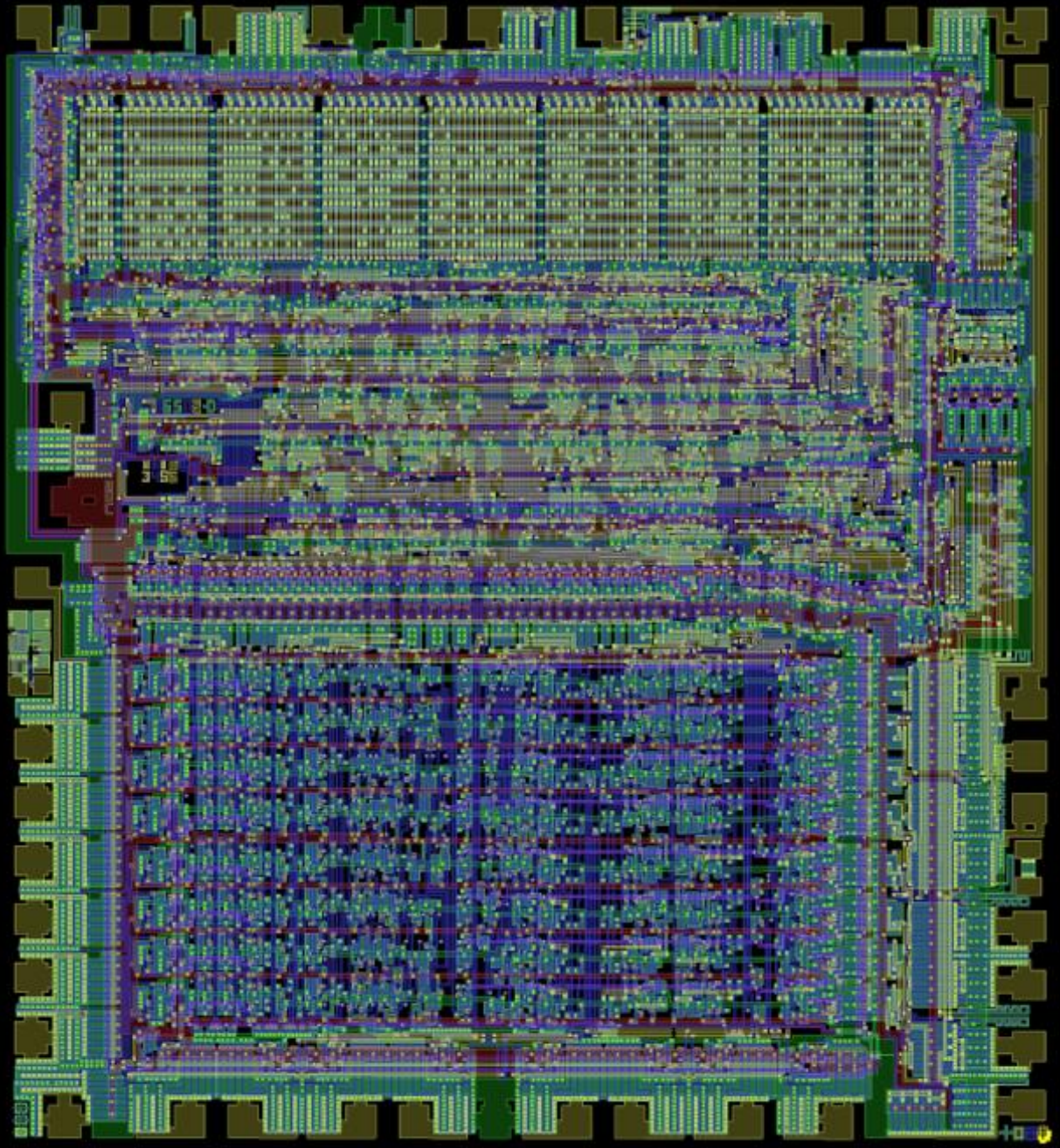
Nov. 23, 2009



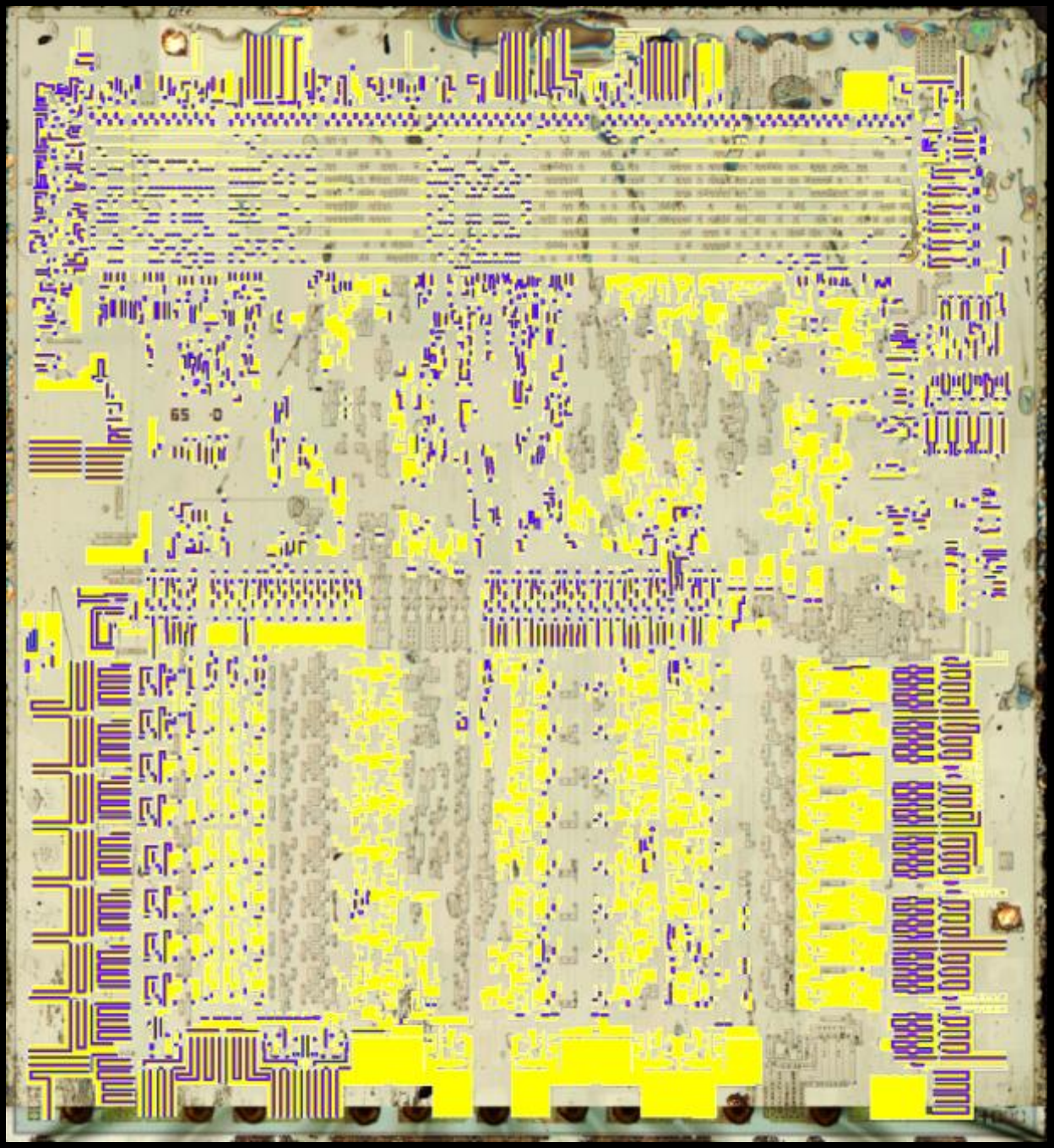
Nov. 30, 2009



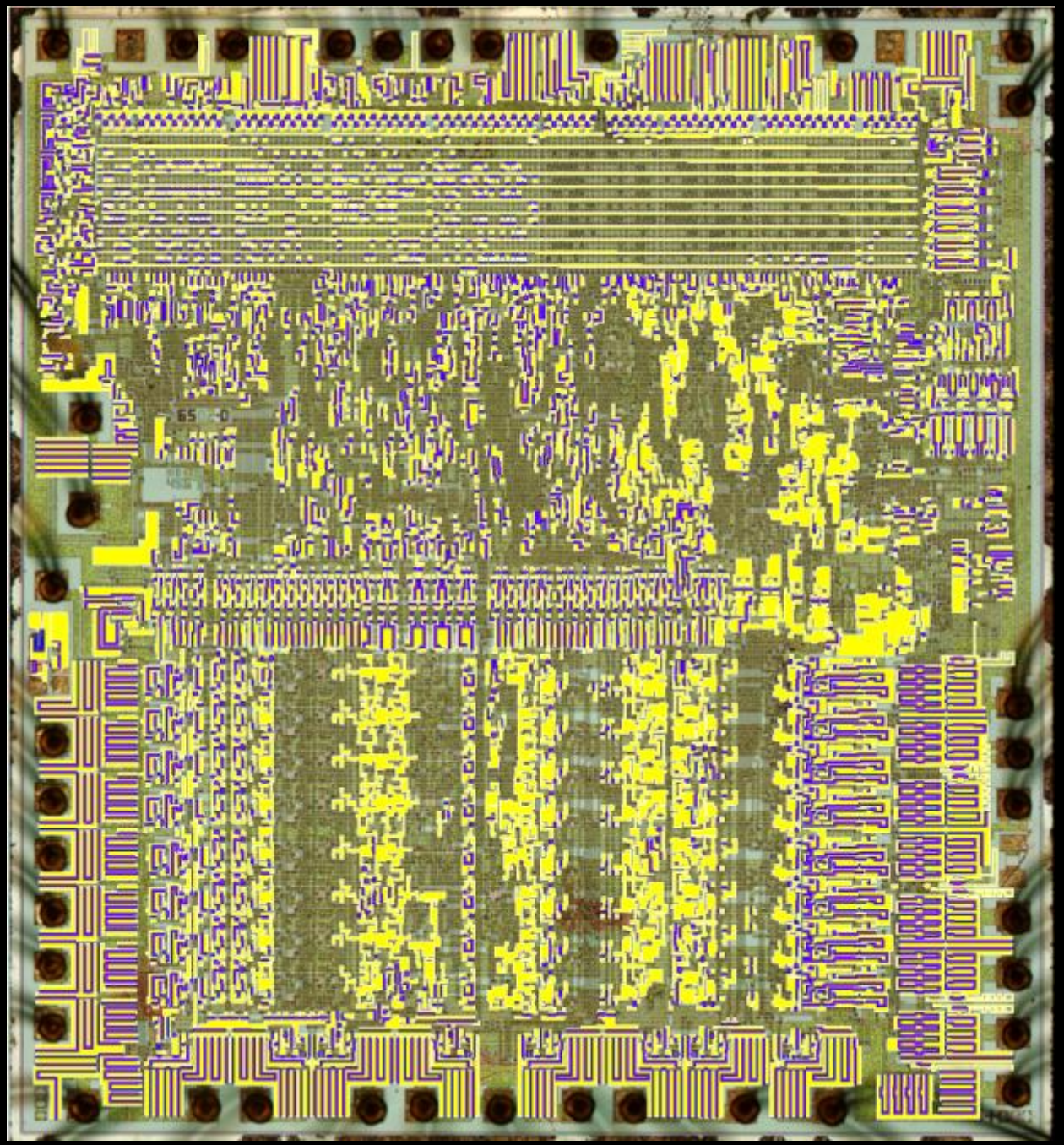
Dec. 4, 2009



Dec. 11, 2009



Nov. 30, 2009



Dec. 4, 2009

Live Demo

- Interactive 6502 chip simulation

Emulation & Simulation

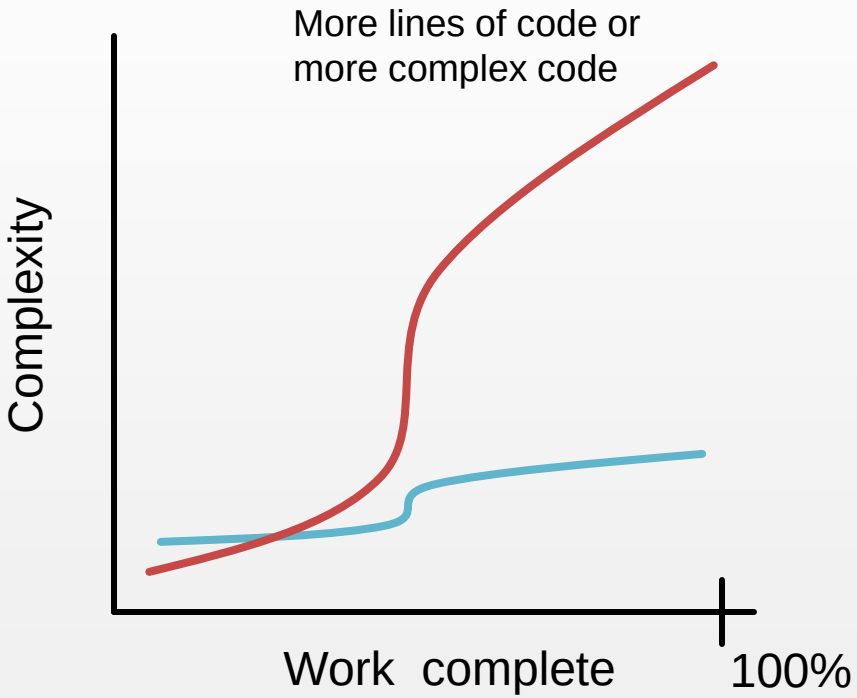
- George Phillips, “Simplicity Betrayed”, Communications of the ACM, Vol. 53 No. 6, pages 52-58. Full text

- TRS-80 screen display
- Simple characters
  - Byte in memory → character on screen

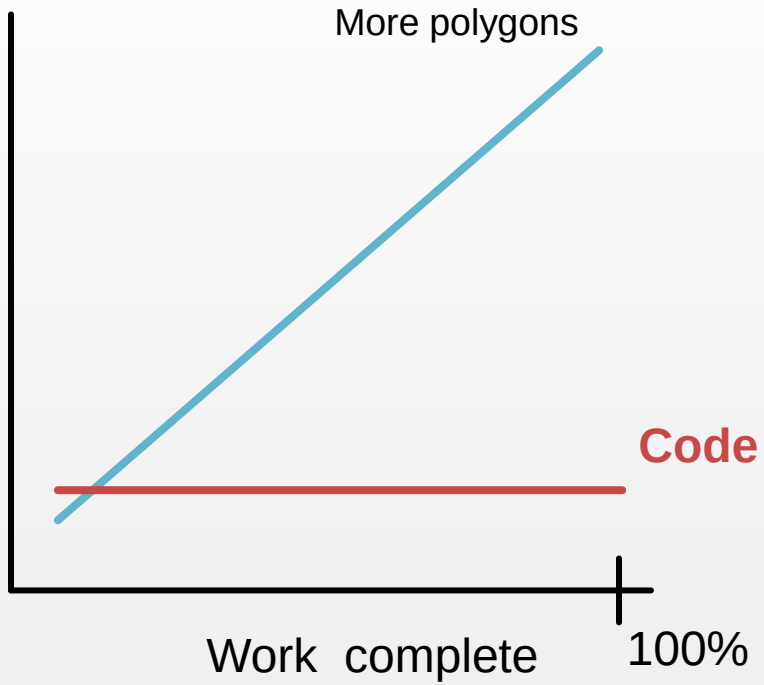
- Easy to approximate
- Extremely difficult to emulate accurately

Emulation & Simulation

- Complexity: **Code**, **Data**



Emulation

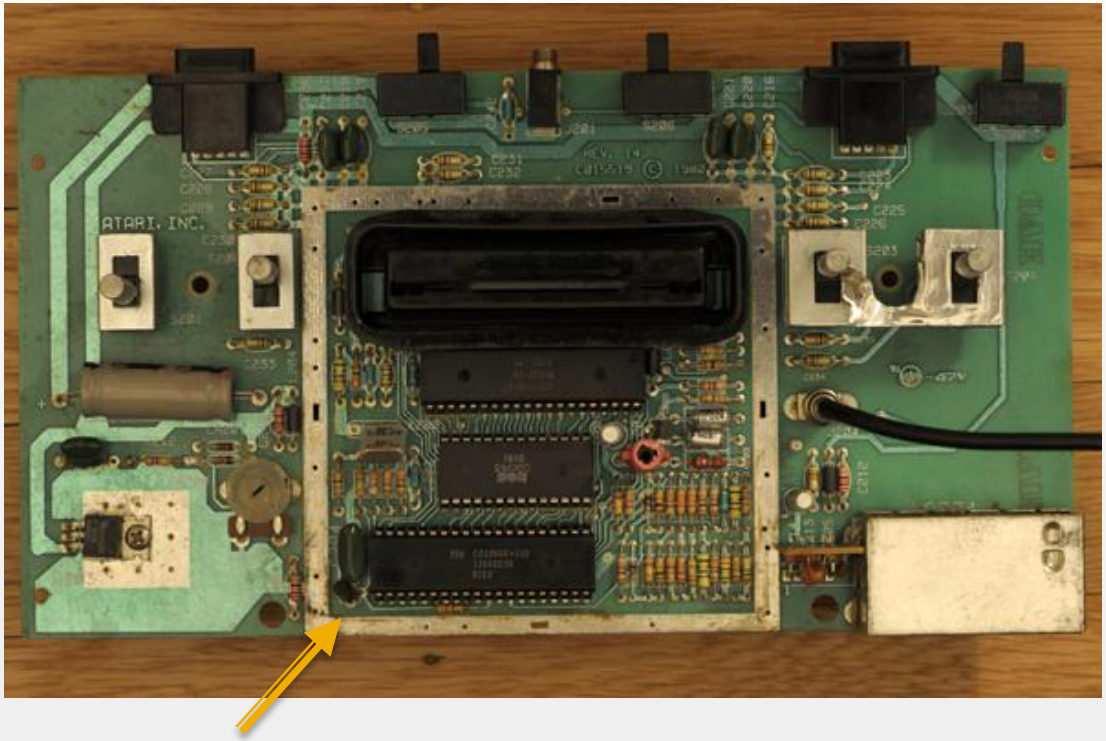


Simulation

But wait… there's more!

- Verifying bytes is kinda dull
- The 6502 has friends

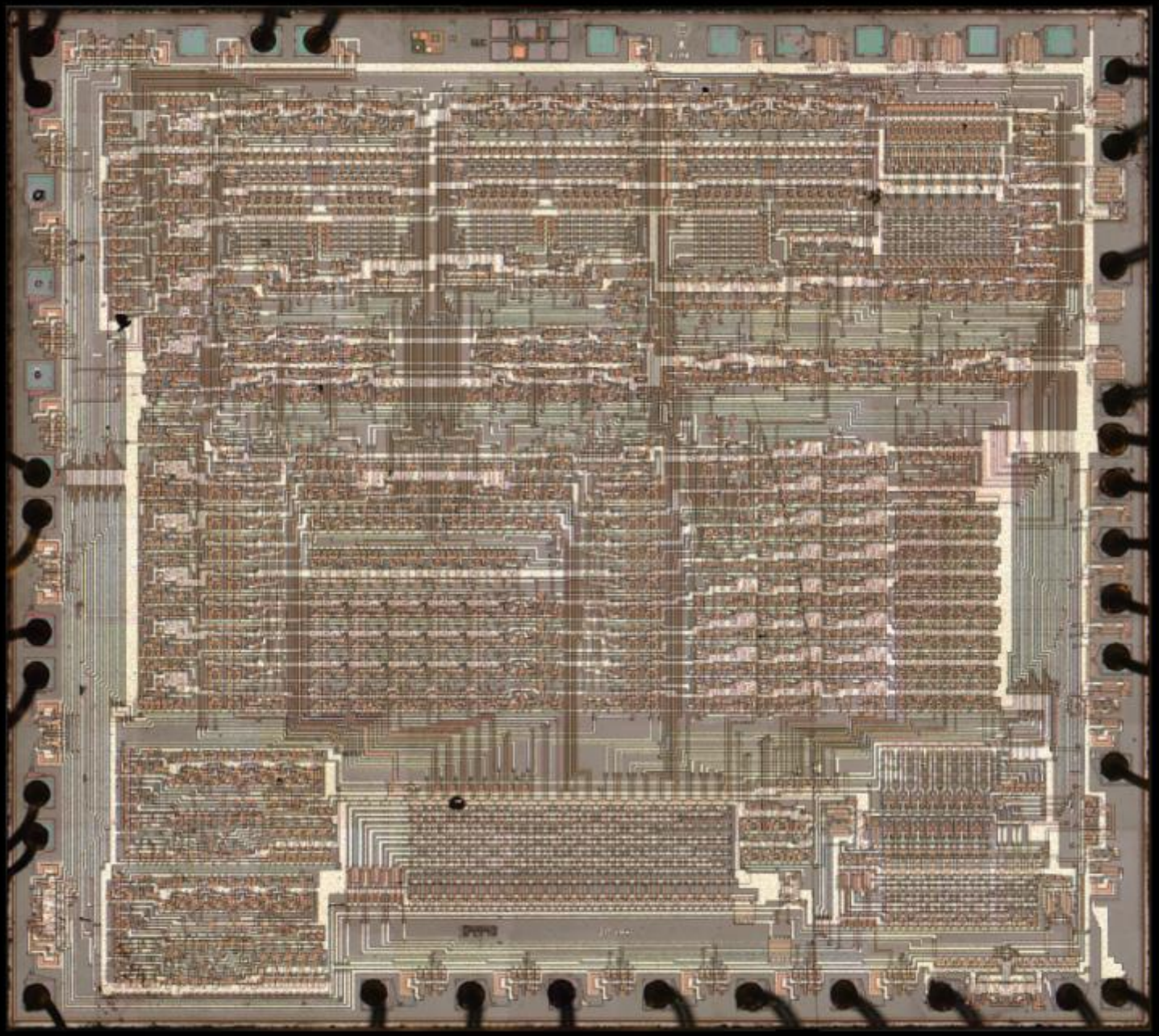
Atari 2600
game system

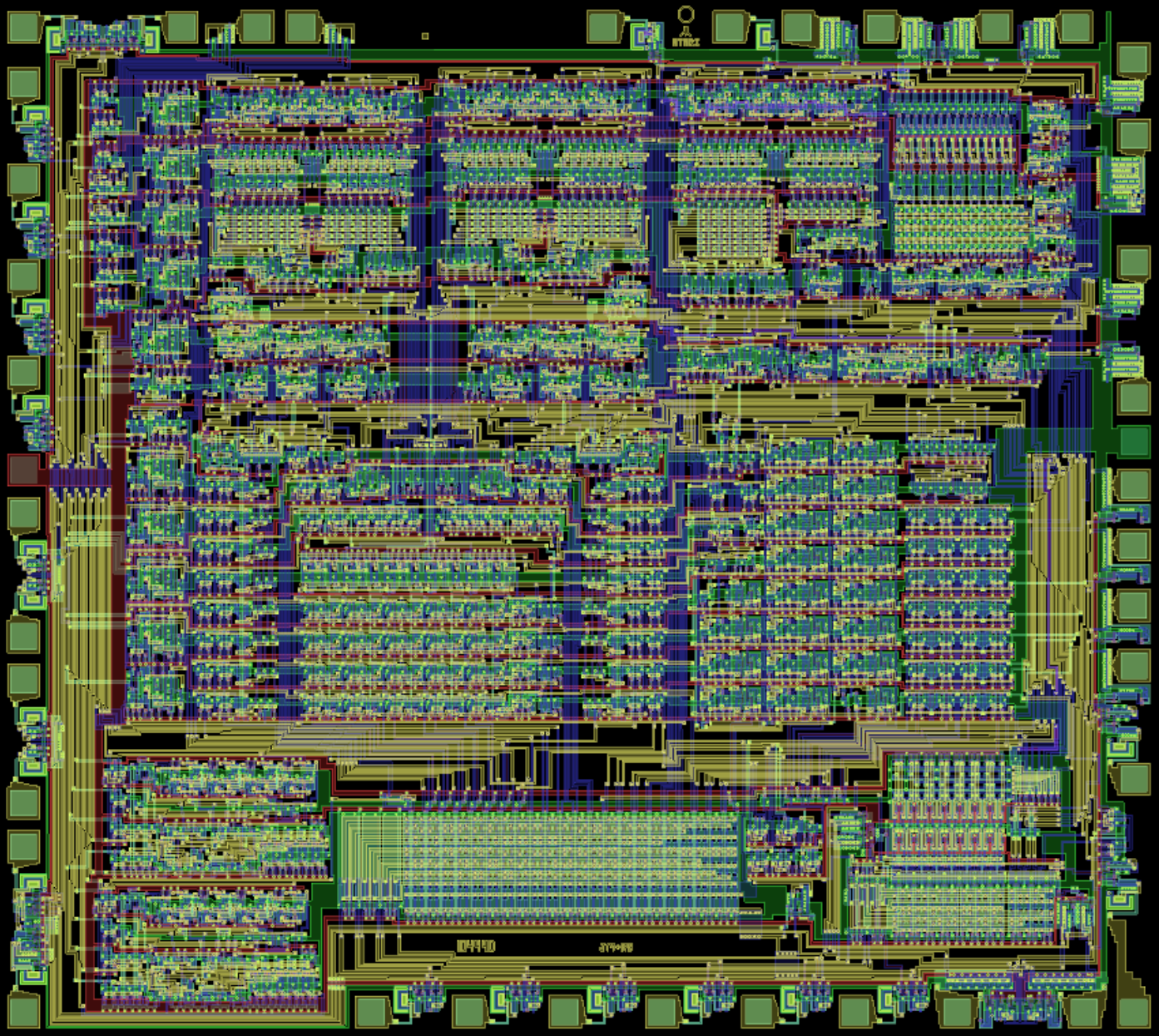


Atari 10444D, aka. TIA (Television Interface Adapter)

Atari TIA

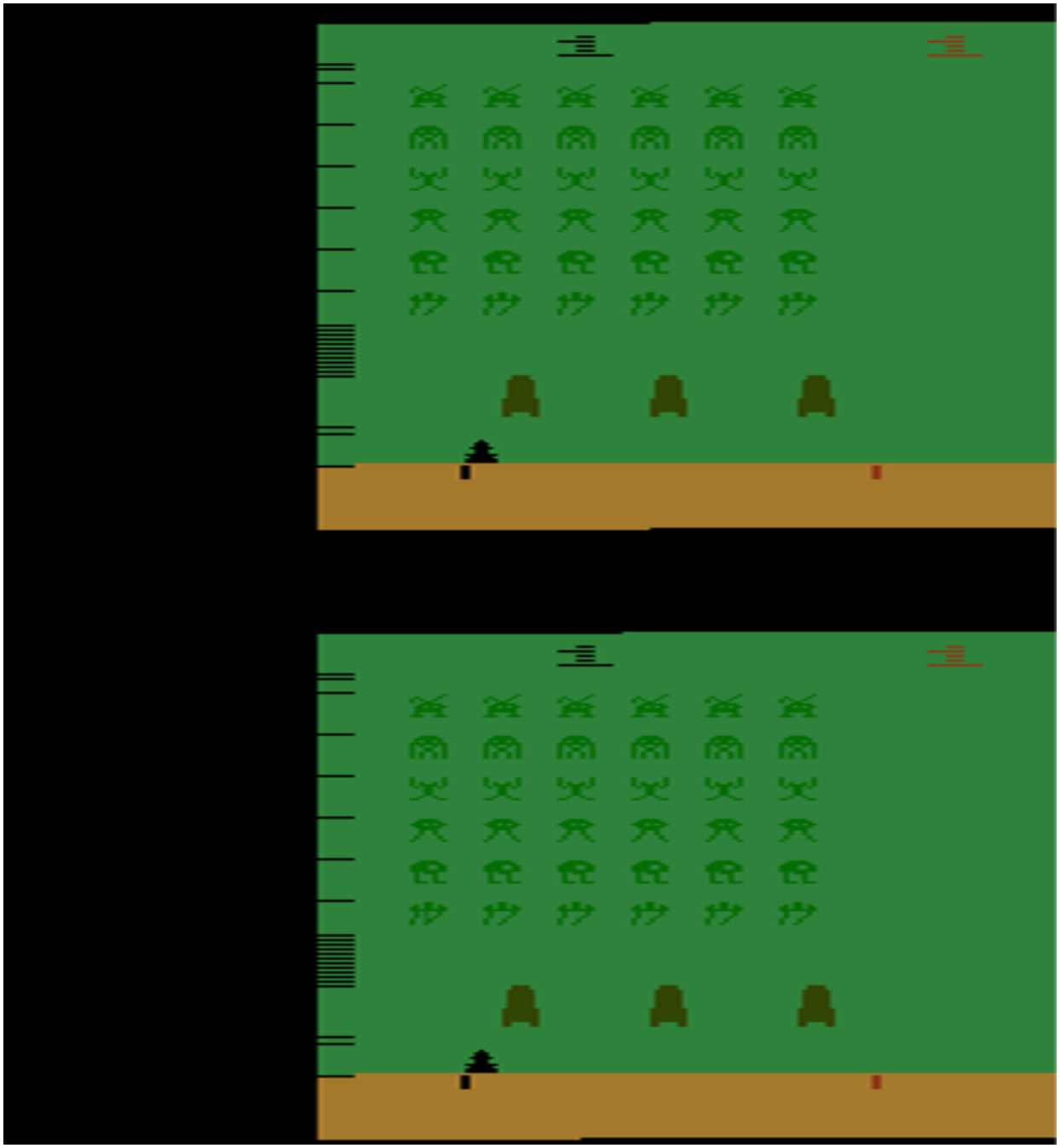
- Makes video signal
  - Made my first pixels ☺
- Sprite engines. No framebuffer
  - Framebuffers cost $60,000
- We know how it connects to the 6502





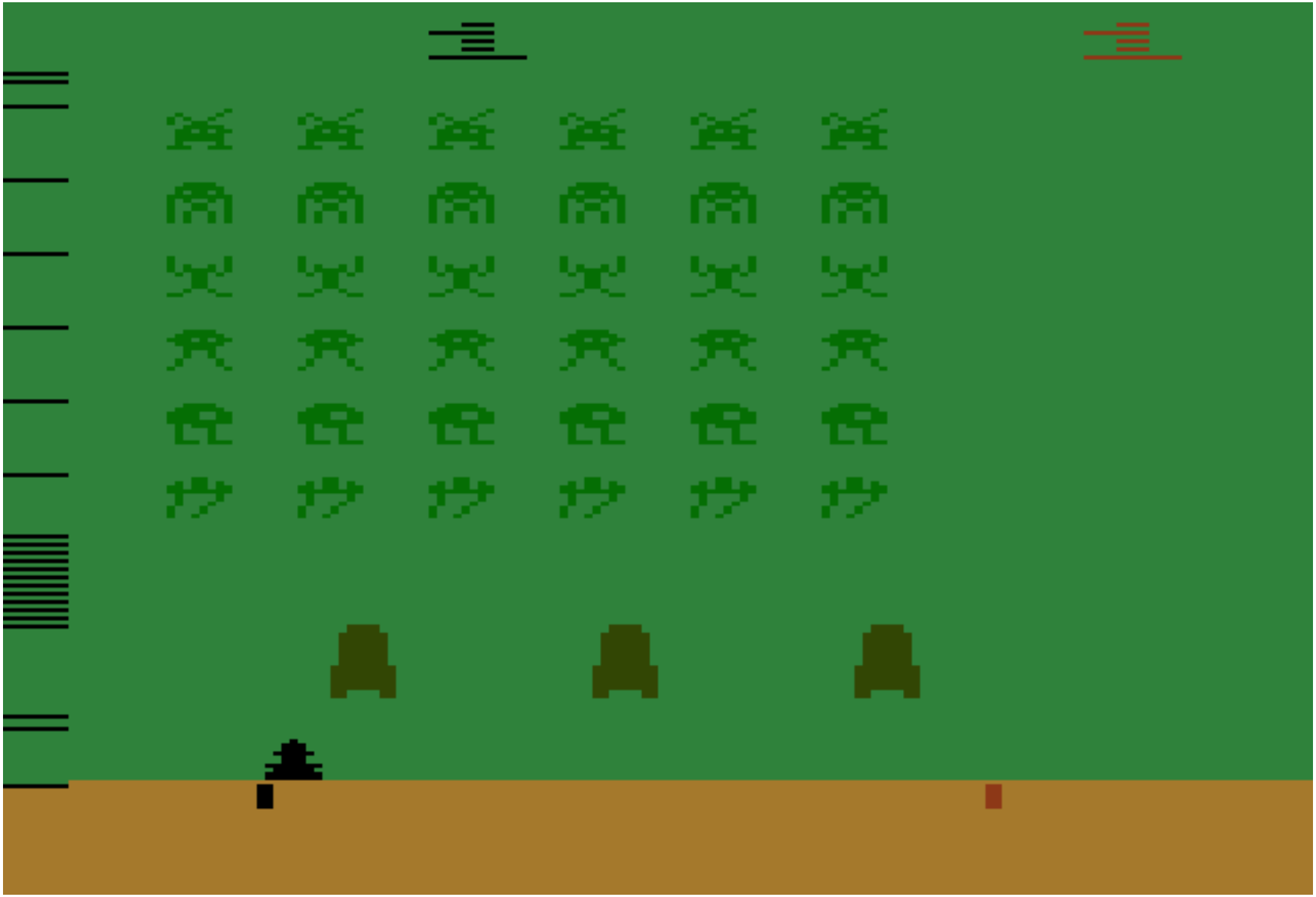
Connect two Chip Simulations

- 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

http://stella.sourceforge.net

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!

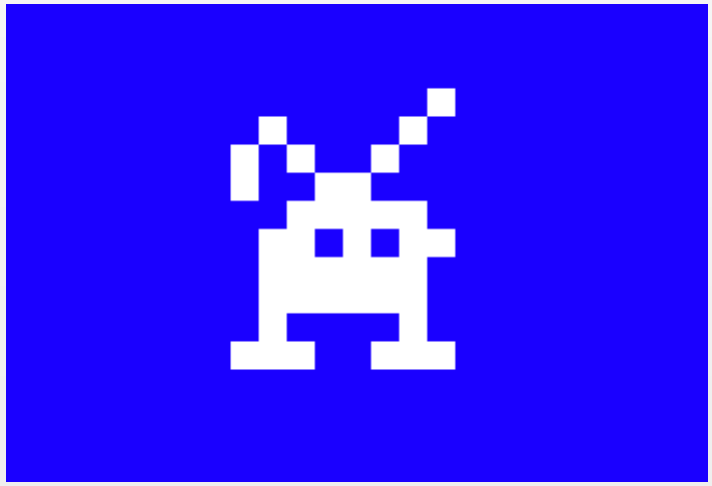
Download, Contribute!

- 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

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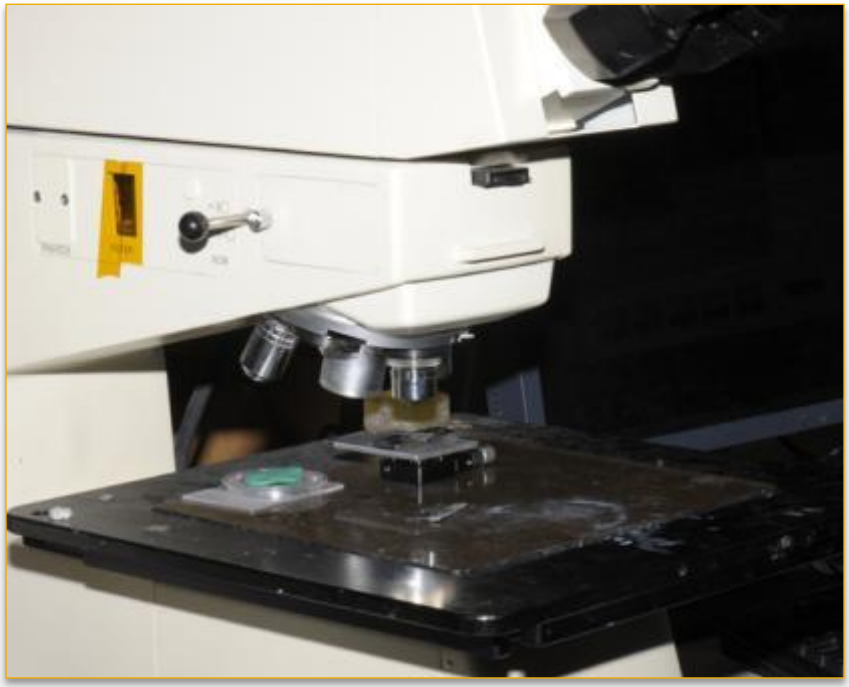
- Andrew Volk, Peter Stoll, Paul Metrovich, "Recollections of Early Chip Development at Intel", Intel Technology Journal Q1, 2001
- Tim McNemey, Intel 4004 Project, http://www.4004.com
- Erik Klein, http://www.vintage-computer.com
- “Stella” Atari 2600 emulator. stella.sourceforge.net
- Wikimedia Commons. 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
  - Altair 680
  - Defender
  - Amiga
    Apple Mac
  - W. Mensch
    C. Peddle, et. al.
- MOS: 6502 – 6507 – 6510
  - Commodore PET, C64
    Apple I, II
  - Atari 2600, 400 / 800
  - Asteroids
  - Nintendo NES
- Intel: 4004 – 8008 – 8080 – 8085 - 8086 – 80186, x286
  - Altair 8800
  - F. Faggin
    M. Shima
  - Space Invaders
  - PCs….
- Zilog: Z80 – Z8000 – Z80000 – Z380
  - TRS-80
  - ColecoVision
  - Pac-Man, Galaga, Xevious, …

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

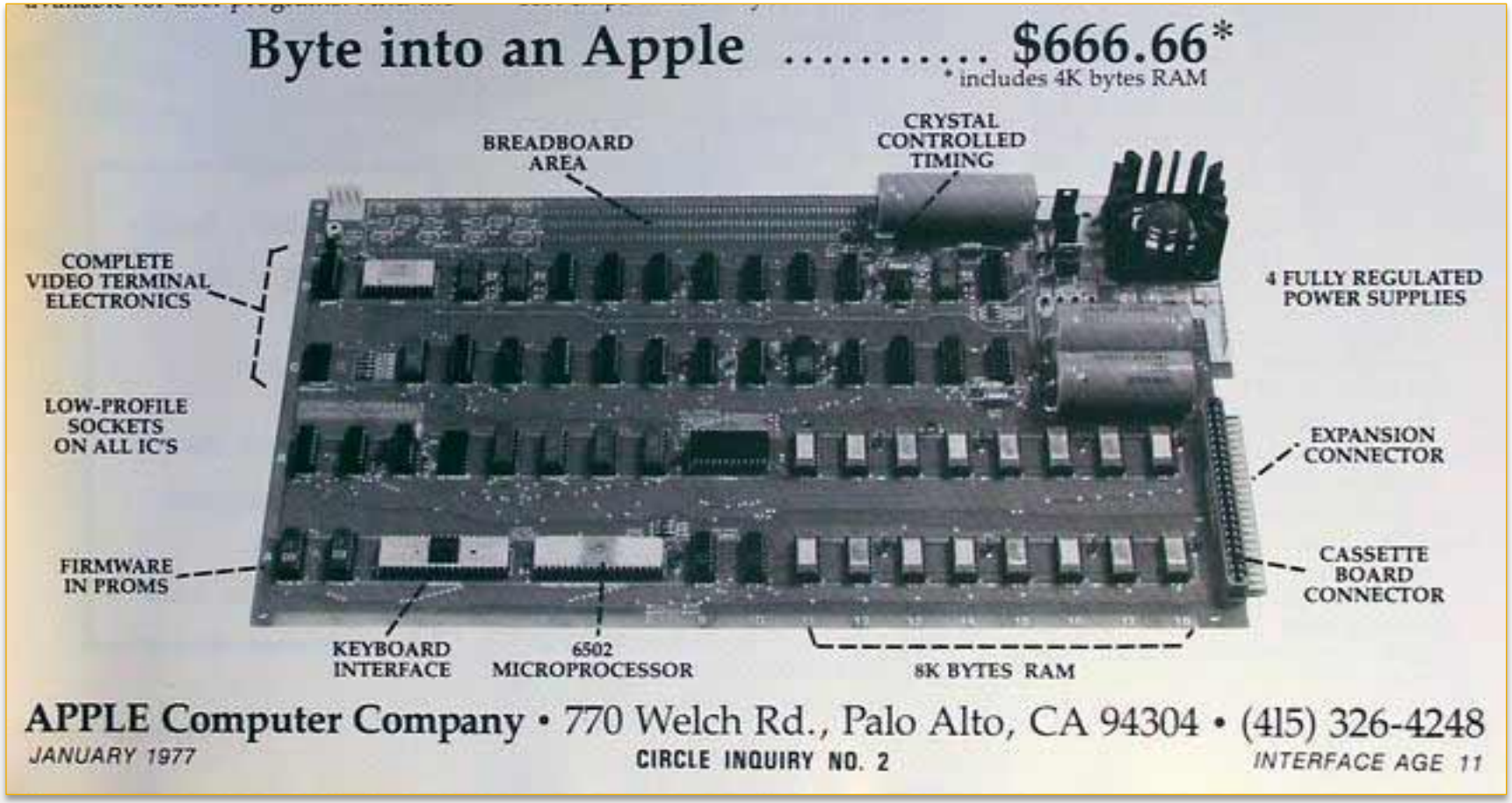
- 100% accurate 6502 in simulation
  - Could make an actual chip
  - No guesswork. Complete information

- 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

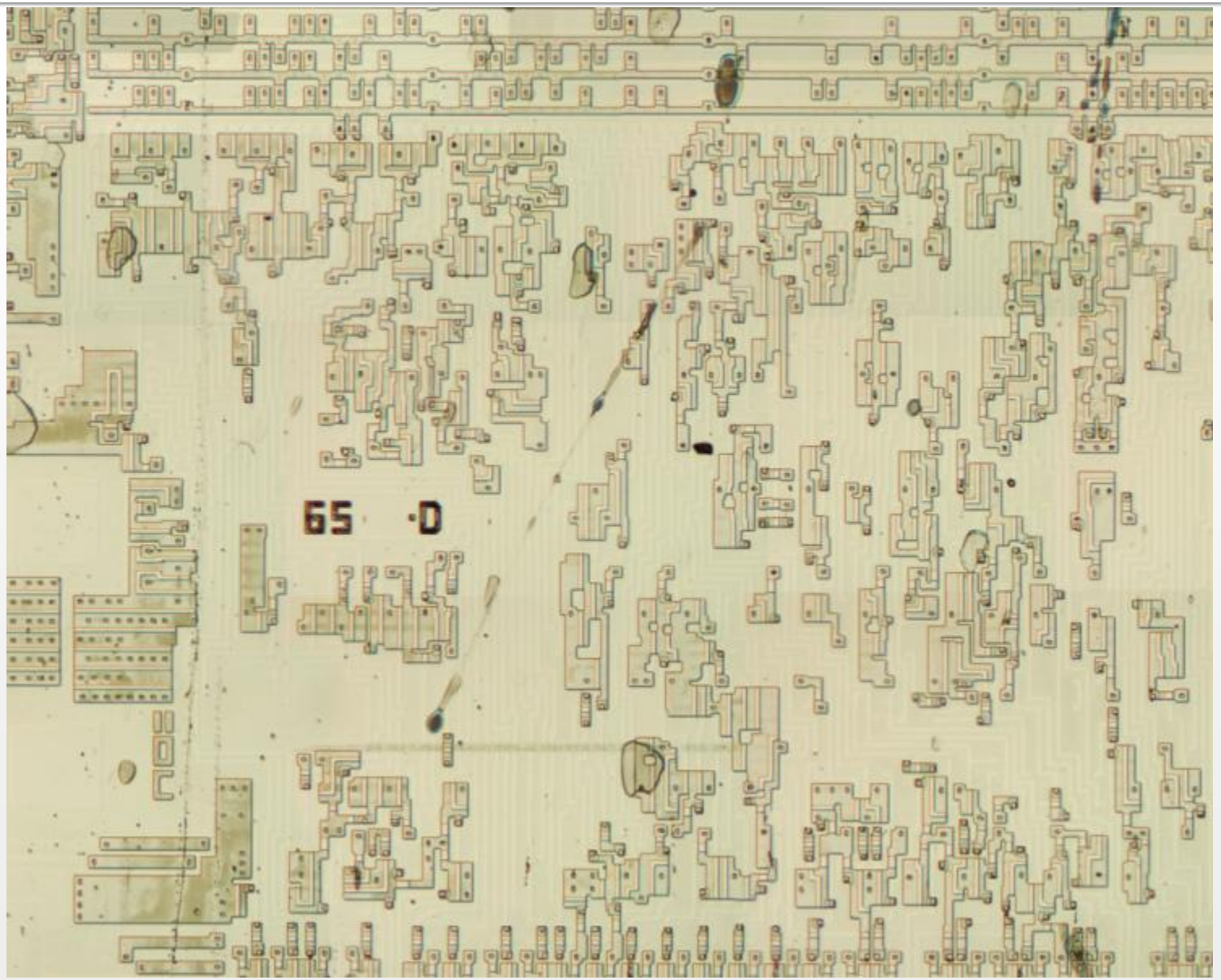
Apple I: 6502 CPU



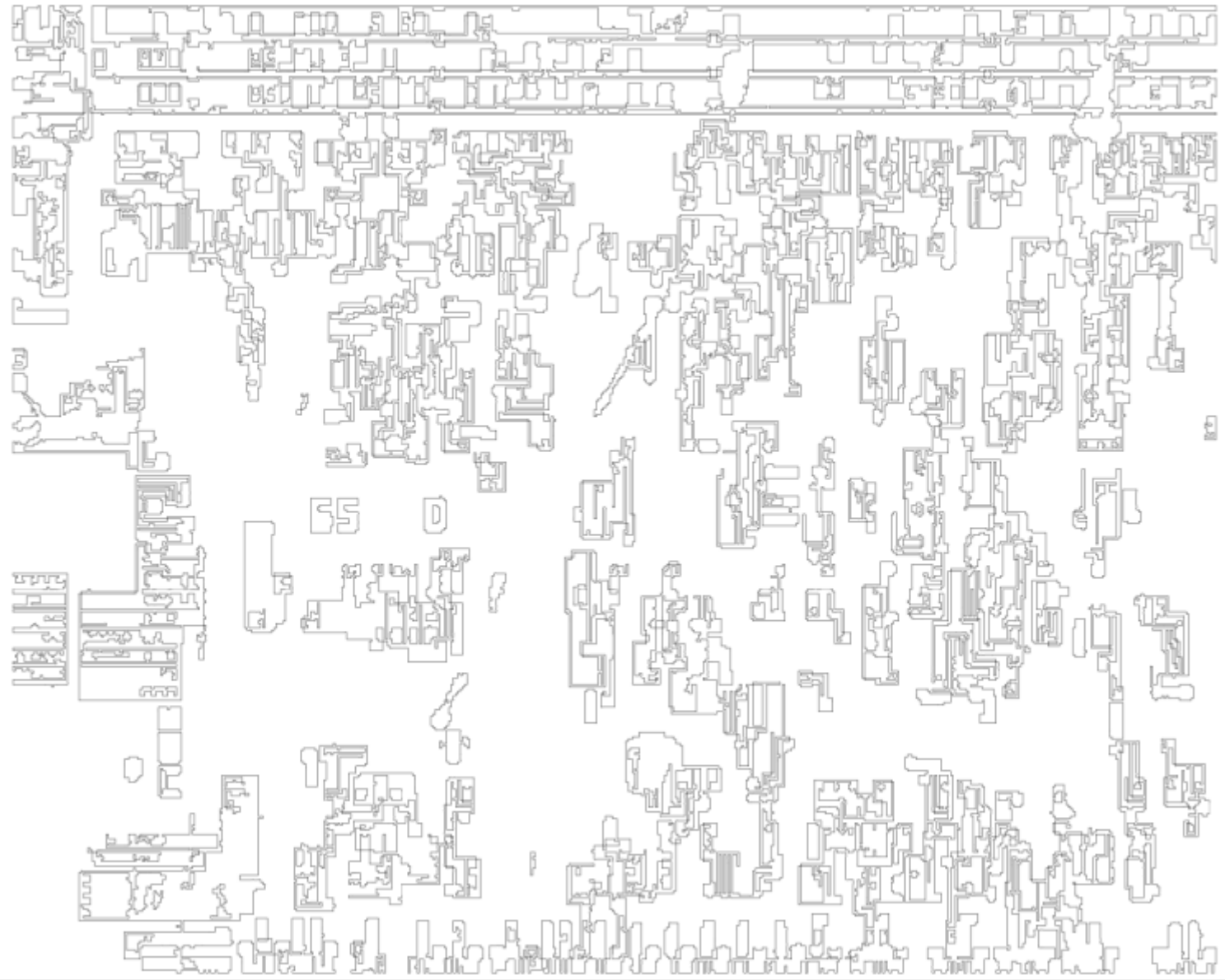
Apple I motherboard, 1977

Byte Magazine, 1977 [Klein] CCL 1.3

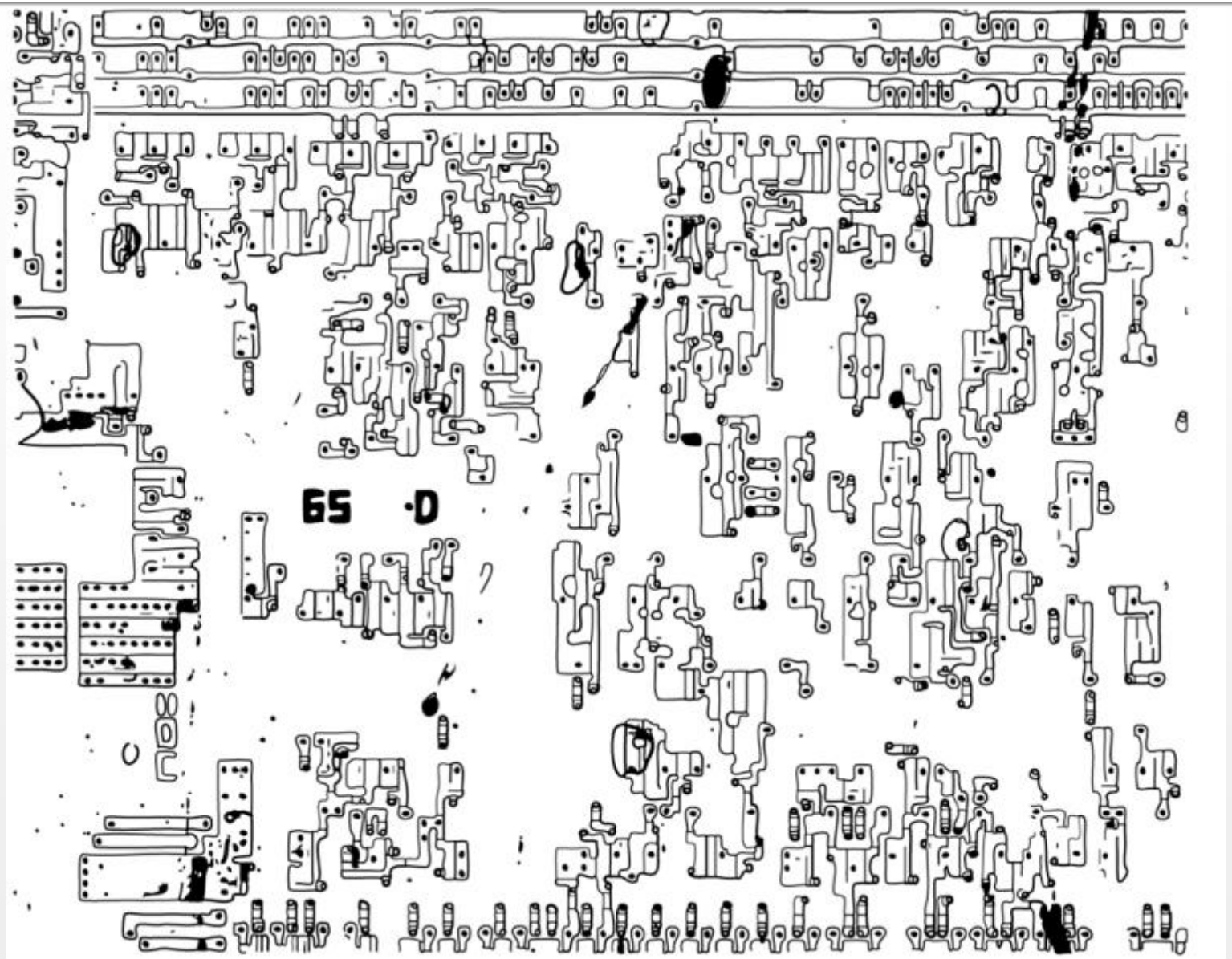
Automatic Vectorization - Input



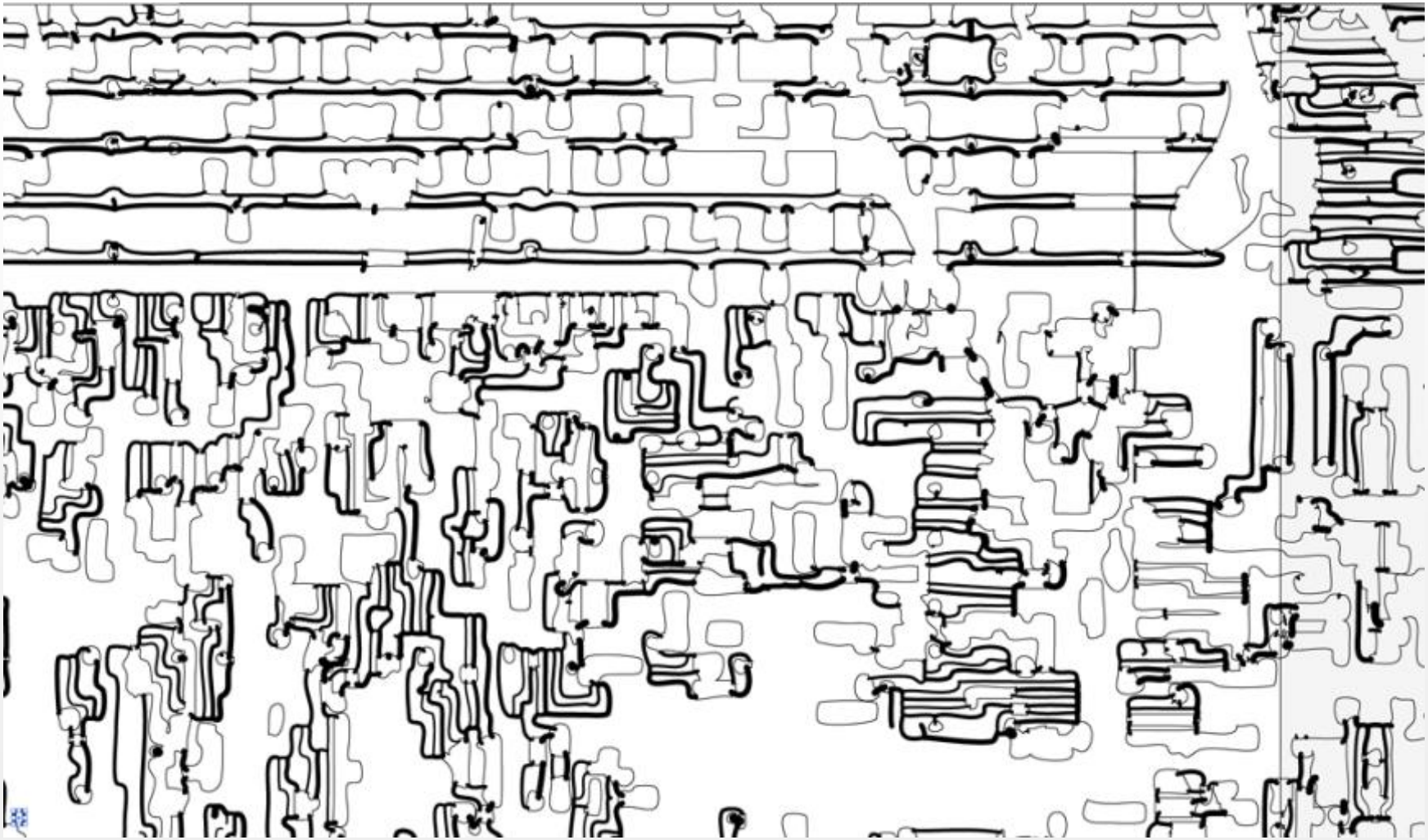
Automatic Vectorization



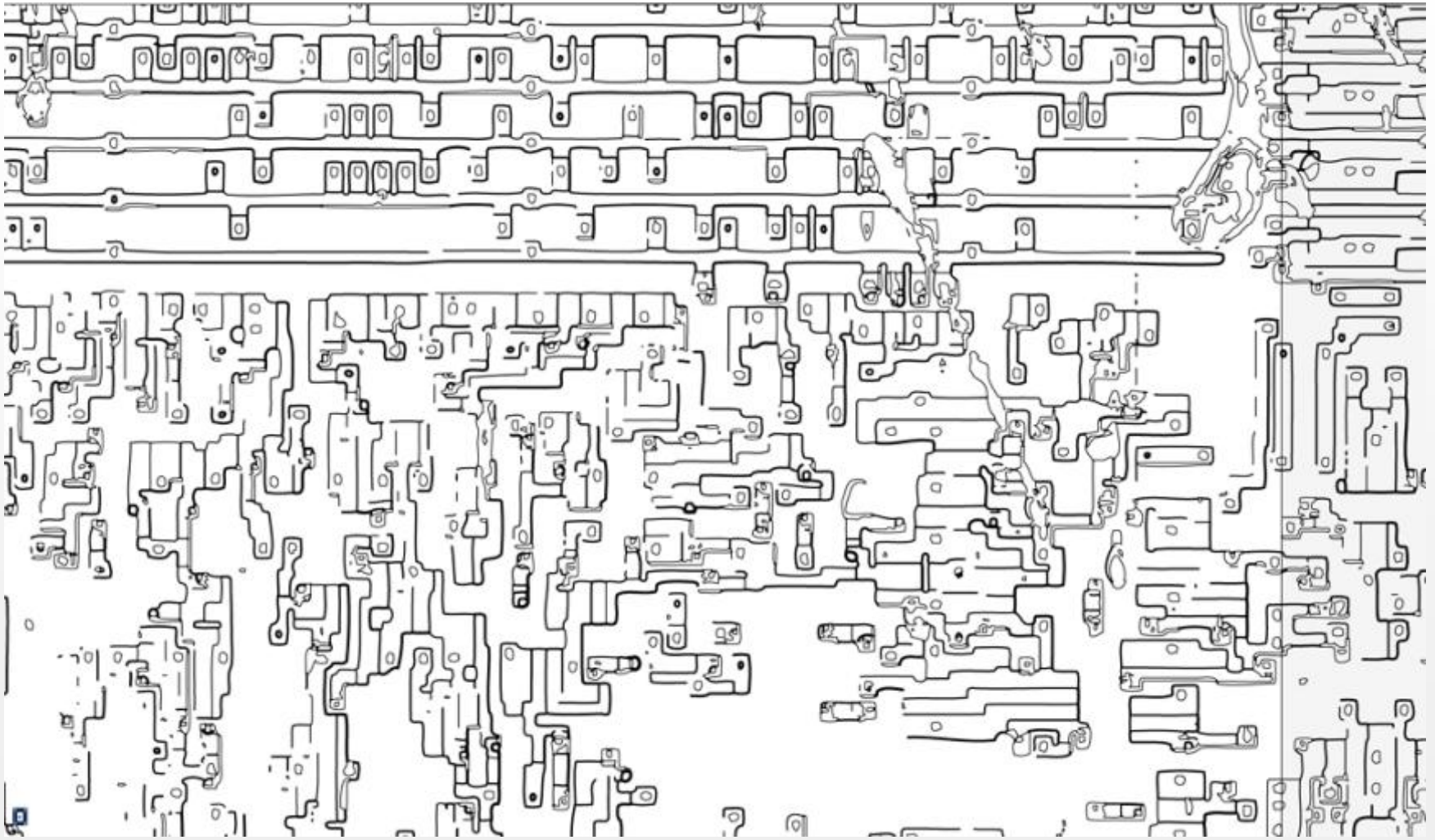
Automatic Vectorization – oops



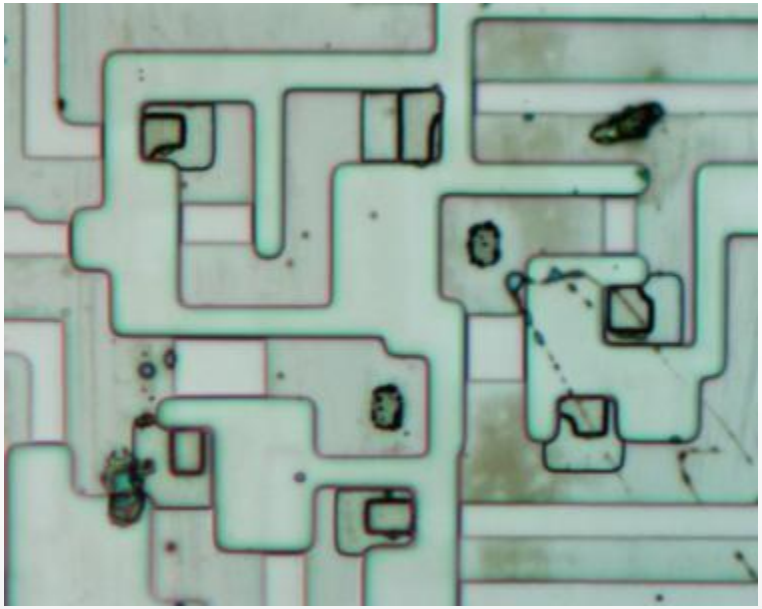
Automatic Vectorization – Hah!

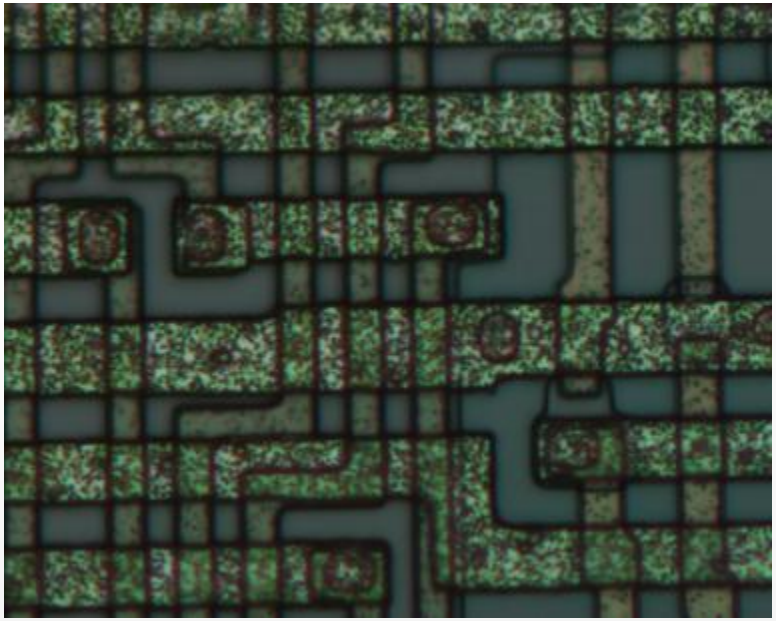


Automatic Vectorization

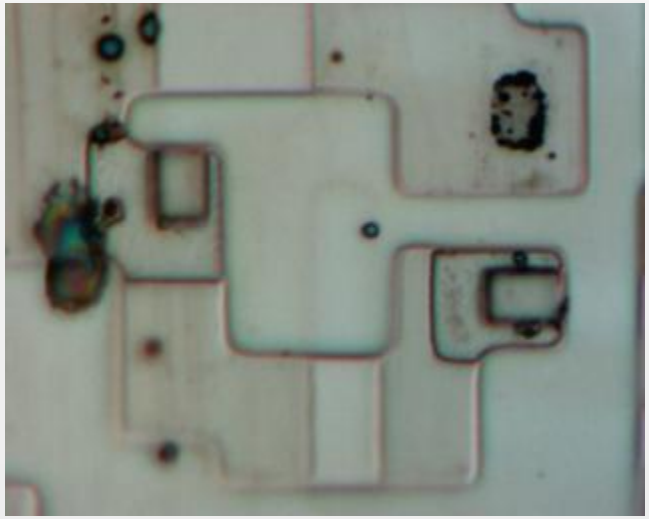


High Magnification Shots





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 framebutter (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