Visualizing a Classic CPU In Action: The 6502

SIGGRAPH 2010
July 27th, 2:00 pm, Theater 411
Greg James
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Brian Silverman
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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MOS Technology’s
6502 CPU
Released 1975
Apple I, II
Commodore PET, C64
Atari 2600 (6507)
Atari 400, 800
Nintendo NES
Wall Art: 6502 die shot

Jobs, Wozniak, and ...

The 6502

[Klein] CCL 1.3
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
1981. I was eight

- Atari 2600 game system
- Apple II+
1981. I was eight

- Atari 2600 game system
- Apple II+
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

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

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

- Intel 4004 35\textsuperscript{th} 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

Registers

Instruction Decode

ALU

Images by Brian Silverman, Barry Silverman, CCL1.2
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+
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
Live Demo

- Interactive 6502 chip simulation

- TRS-80 screen display
- Simple characters
  - Byte in memory → character on screen
- Easy to approximate
- Extremely difficult to emulate accurately
Complexity: **Code, Data**

- More lines of code or more complex code
- More polygons

**Emulation**
- Work complete
- Complexity

**Simulation**
- Work complete
- Complexity
Verifying bytes is kinda dull
The 6502 has friends

Atari 2600 game system

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

Andrew Volk, Peter Stoll, Paul Metrovich, "Recollections of Early Chip Development at Intel", Intel Technology Journal Q1, 2001


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
  - Pac-Man, Galaga, Xevious, …
  - ColecoVision
6502 Project Timeline

- Start drawing: Nov. 11, 2009
- Finish drawing: Dec. 12, 2009
- Good startup in sim: Dec. 26, 2009
- 2\textsuperscript{nd} 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
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

APPLE Computer Company • 770 Welch Rd., Palo Alto, CA 94304 • (415) 326-4248

CIRCLE INQUIRY NO. 2

JANUARY 1977

EXPANSION CONNECTOR

CASSETTE BOARD CONNECTOR

4 FULLY REGULATED POWER SUPPLIES

Apple I motherboard, 1977

Byte Magazine, 1977 [Klein]  CCL 1.3
Automatic Vectorization – oops
Automatic Vectorization – Hah!
Automatic Vectorization
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](http://sophia.javeriana.edu.co/~ochavarr/computer_graphics_history/historia)