Apollo Guidance Computer

Background on the Apollo Guidance Computer (AGC)

Background of the AGC

- MIT Instrumentation Laboratory (later named Draper Labs)
- 16 bit wordlength, 1 parity bit
- Block 1 was used for unmanned flights in orbit & Block 2 went to the moon
  - Same architecture
  - Differently sized memory
  - More instructions in Block 2
  - Both used core rope memory
- AGC was one of the 1st to use ICs.
  - Block 1 used 4100 single 3-input NOR gates
  - Block 2 used 2800 dual 3-input NOR gates

Block 1 vs Block 2

Block 1 had:

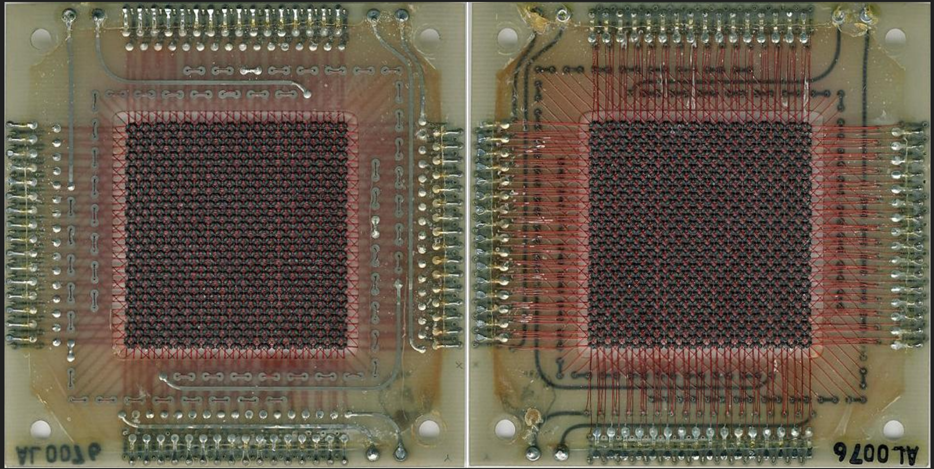
- 1 kiloword in erasable
- 24 kilowords in fixed memory
- 11 instructions + EXTEND

Block 2 had:

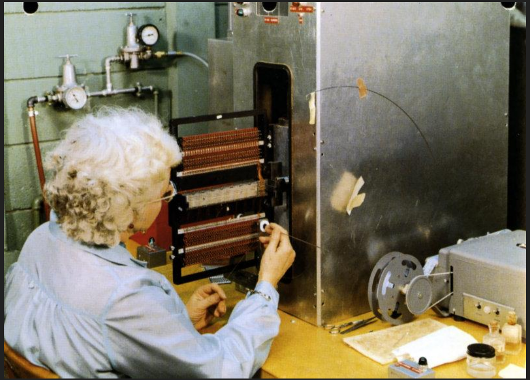
- 4 kilowords in erasable
- 32 kilowords in fixed memory
- 34 instructions
  (including original 11)

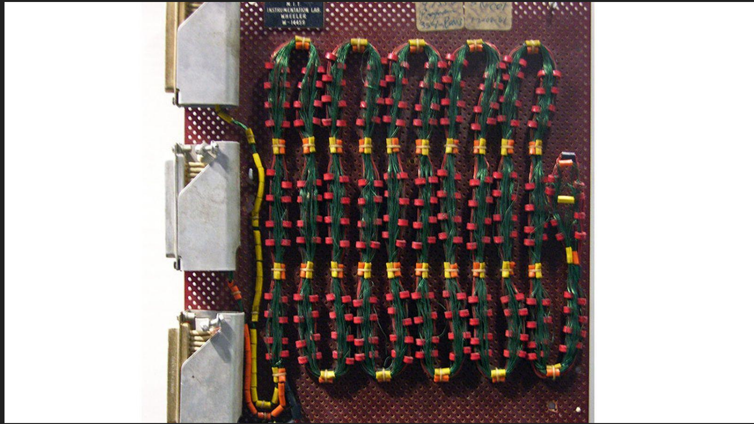
Memory

- Two types of memory:
  - Fixed
  - Erasable
- **Very tight** on memory
- Used 34 banks of fixed memory
  - Bank 0 = Erasable
  - Fixed-Fixed: Banks 1 and 2 of Fixed Memory
  - Fixed-Switchable: Register holding value of bank to address into
  - F-bank could hold extra addressing bits
- Little Old Lady Memory (core rope memory- fixed)



Erasable memory



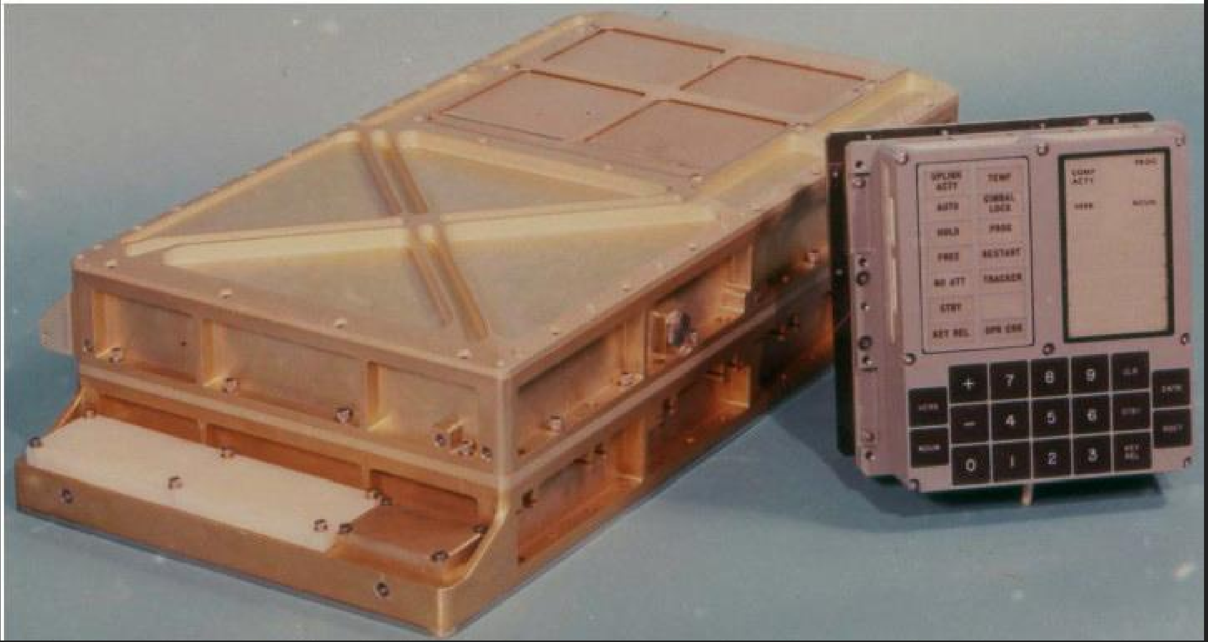


Core rope memory (Fixed)

Interface

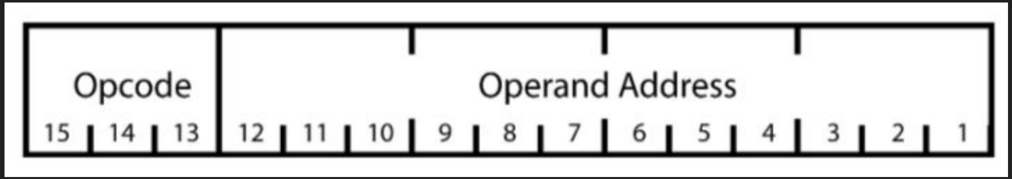
DSKY interface:

Astronauts could reprogram instructions (in erasable memory) through DSKY



Instructions

- Instructions were mostly stored in fixed memory
- Op Code: Operation code, 3 bits in Block 1.
- Quarter Code: Extra information for the operation. Differentiates Op Codes
- Peripheral Code: Specifically for specifying which I/O operation



Format was: **(Op code+Quarter Code) + K**

K = 12 or 10 bit Address

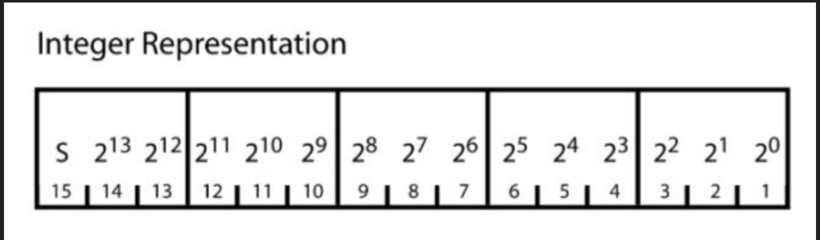
Example Block 1 instructions

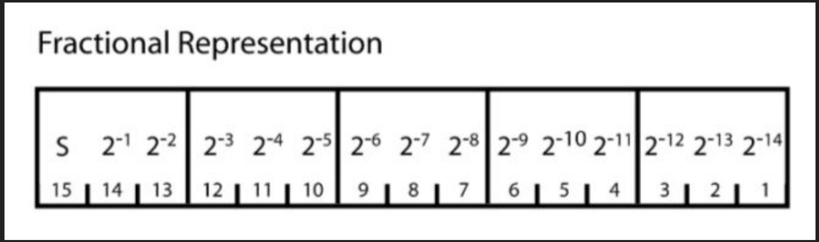
1. TC: Transfer Control (jump)
2. TS: Transfer to storage
3. CCS: Count, Compare and Skip (similar to branch)
4. INDEX: Add a constant to program counter
5. CS: Clear and subtract, get one’s complement
6. XCH: Exchange between register A & Memory[address]
7. MASK: bit-wise AND operation
8. ADD
9. MULTIPLY
10. DIVIDE
11. SUBTRACT

One’s Complement

- Two’s complement was still being developed (~1963).
- -0 (15’b111111111111111) and +0 (15’b000000000000000) were useful for CCS, the 4-way branch
  - +0, -0, >0 or <0
- To represent something as negative in 1’s complement, have a sign bit (1 → negative) and NOT the rest of the bits

Scaling factors and fractions



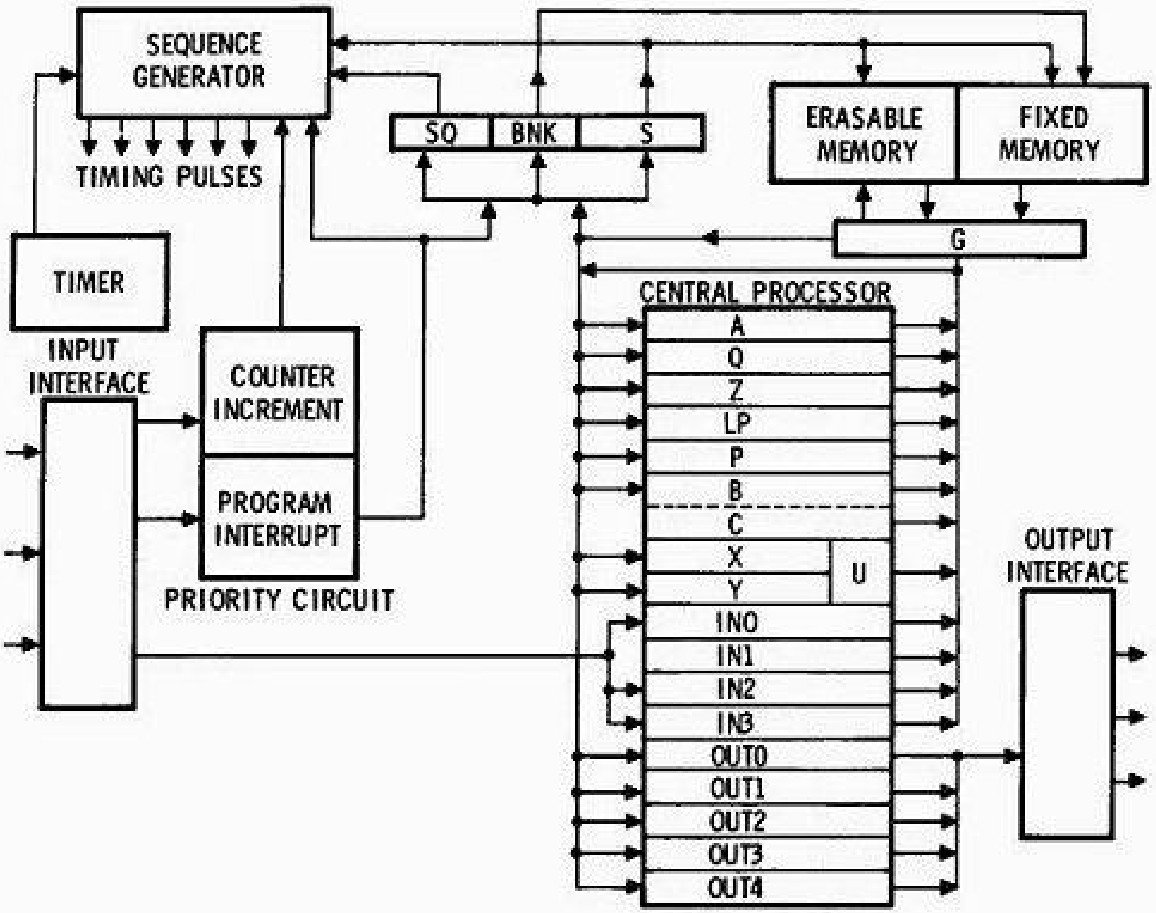


“Here, maintaining the magnitude, or scaling factor, was a ***burden imposed upon the programmer****”*

-The Apollo Guidance Computer: Architecture and Operation

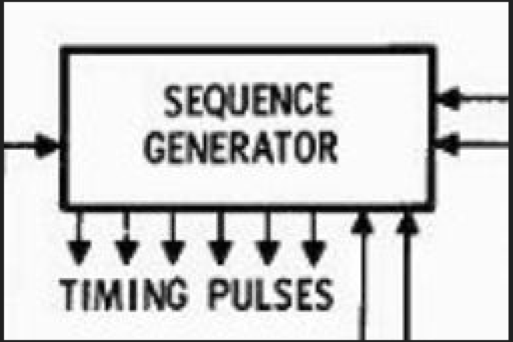
Our implementation

AGC GENERAL BLOCK DIAGRAM



We adapted it for behavioral Verilog.

Control logic



We implemented: (behavioral Verilog)

11 timing pulses control the sequence of events in writing/reading/computing

They implemented: (NOR gates)

Cycles of 12 timing pulses, with each cycle taking 11.72 μS

822

Lines of code

11

Block 1 Instructions

3

Block 2 Instructions

Original source code

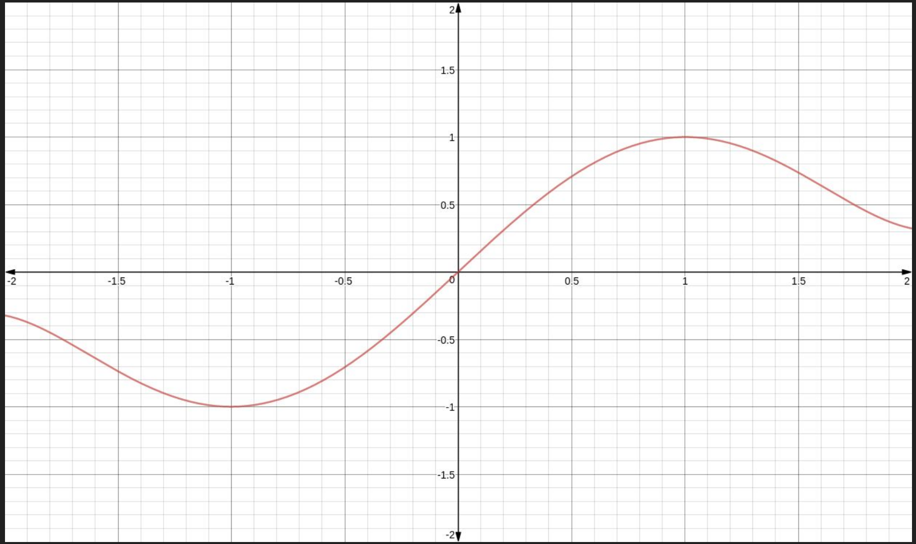
The original assembly machine code has been put onto GitHub[1] to show the world how we got to the moon. This particular snippet is what we used to show our AGC works.

```
# Page 1207
                BLOCK   02

# SINGLE PRECISION SINE AND COSINE

                COUNT   02/INTER

SPCOS           AD      HALF
SPSIN           TS      TEMK
                TCF     SPT
                CS      TEMK
SPT             DOUBLE
                TS      TEMK
                TCF     POLLEY
                XCH     TEMK
                INDEX   TEMK
                AD      LIMITS
                COM
                AD      TEMK
                TS      TEMK
                TCF     POLLEY
                TCF     ARG90
POLLEY          EXTEND
                MP      TEMK
                TS      SQ
                EXTEND
                MP      C5/2
                AD      C3/2
                EXTEND
                MP      SQ
```

[1] https://github.com/chrislgarry/Apollo-11

Hasting’s Approximation of a sine wave

$$\sin(pi/2*x) = C_1x + C_3x^3 + C_5x^5$$

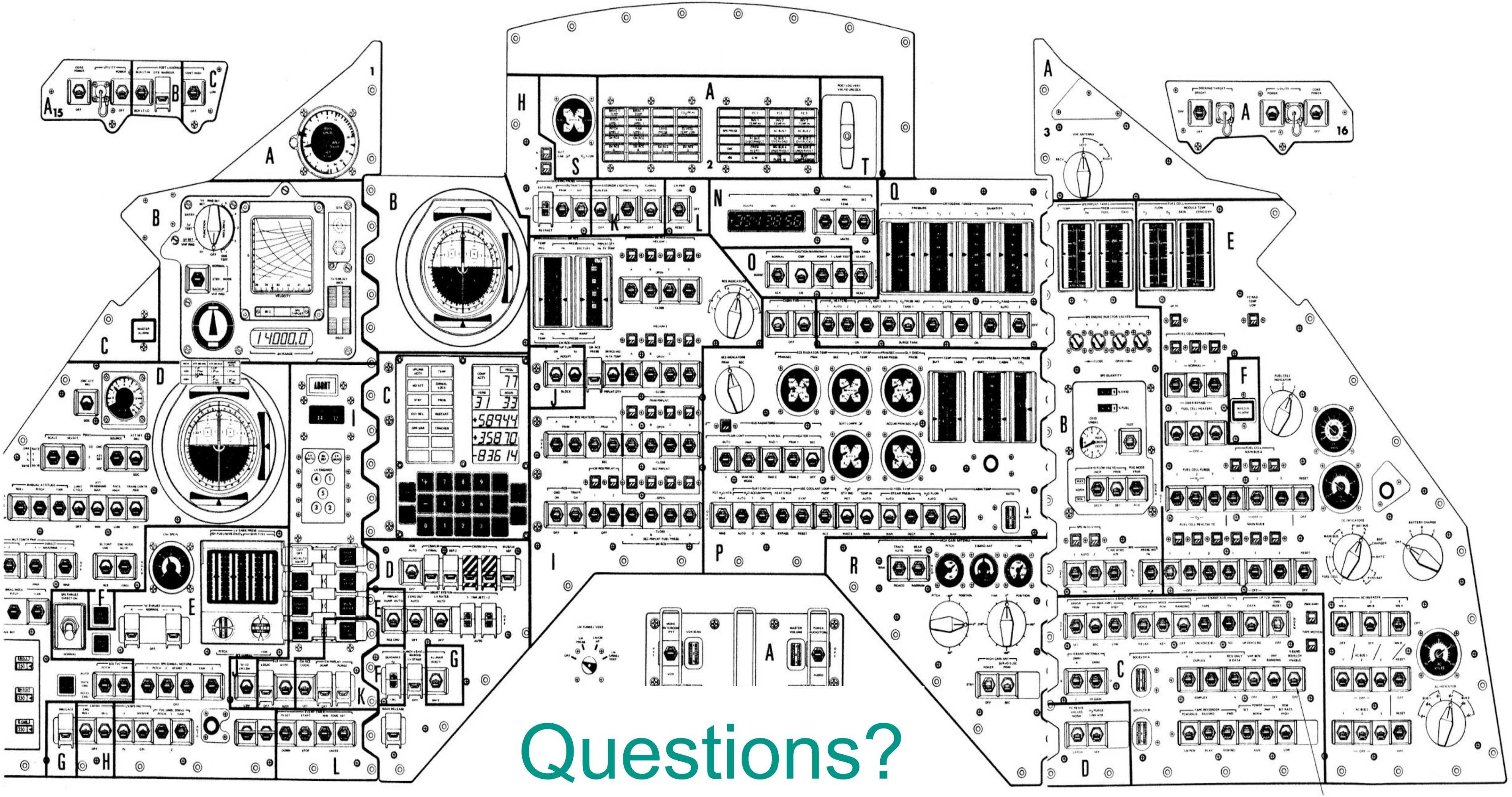


$C_1 = 1.5706...$
$C_3 = -0.6432...$
$C_5 = 0.0727...$

Results

X	sin(x)	Our sin(x)
1/4	0.7071	0.8053
1/8	0.3827	0.3951
1/16	0.1951	0.1966
-1/8	-0.3827	-0.4295
3/16	0.5556	0.5974

APOLLO COMMAND MODULE MAIN CONTROL PANEL



Questions?