“Experience is what you get...
...when you don't get what you want.”

Debugging
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Debugging

As soon as we started programming, we found to our surprise that it wasn't as easy to get programs right as we had thought. Debugging had to be discovered. I can remember the exact instant when I realized that a large part of my life from then on was going to be spent in finding mistakes in my own programs.

– Maurice Wilkes (1949)

Outline

What is “Debugging”?

Programming languages

- **Whitespace**
- **INTERCAL**
- **M**

A debugging story

Conclusions

What is “Debugging”?

Debugging is resolving a clash between stories

- Your hopeful story of achievement
- The world's sad tale of woe

The stories look alike!

- At the beginning, they both start with main()...
- Key step: finding the divergence

Stories are fractal

- You can zoom in on them and get more detail each time
- The divergence is typically a tiny detail
  - You will need to zoom in quite a lot

A Whitespace Program

"Count from 1 to 10" (partial listing)

Features of Whitespace

- Only space, tab, and line-feed encode program statements
- All other characters (A-Z, a-z, 0-9, etc.) encode comments
- Simple stack-based language

Whitespace "Explained"

Statement	Meaning
[Space][Space][Space] [Tab][LF]	Push 1 onto stack
[LF][Space][Space][Space] [Tab][Space][Space][Space] [Space][Tab][Tab][LF]	Set a label at this point
[Space][LF][Space]	Duplicate the top stack item
[Tab][LF][Space][Tab]	Output the current value
...	...

INTERCAL

Features of INTERCAL

- Designed late one night in 1972 by two Princeton students
- Deliberately obfuscated language

Variables

- 16-bit integers, .1 through .65535
- 32-bit integers, :1 through :65535

Operators

- Binary: “mingle”, “select”
- Unary: AND, OR, XOR
  - How are those unary???
  - Simple: AND and's together adjacent bits in a word
- Simplest way to put 65536 in a 32-bit variable?
  - `DO :1 <- #0¢#256`

The language “M”

Features of M

- Also designed in the 1970's
- More widely used than Whitespace, INTERCAL

Variables

- 32-bit integer variables: A, B, C, D, DI, SI, S
- One array, M[]
  - Valid subscripts range from near zero to a large number
  - But most subscripts in that range will crash your program!
- A stack, located in M[], generally pointed to by S

Statements

- Lots of arithmetic and logical operations
- Input and output use a special statement called OUCH!

“C” Example

Print out numbers 1-10

```
for (i = 1; i < 10; ++i)
{
  print_int(i);
}
```

“M” Example

Print out numbers 1-10

Address	Instruction		Comment
00001000	MOV	$1,M[10]	Init loop index
00001004	MOV	$10,M[11]	Init loop limit
00001008	MOV	M[10],A	Fetch loop index
00001012	MOV	M[11],B	Fetch loop limit
00001016	COMPARE	A,B	Compare
00001020	EQUAL?	$1044	If so, done
00001024	PUSH	A	Push loop index
00001028	ADD	$1,A	Increment for next time
00001032	MOV	A,M[10]	Store index for next time
00001036	CALL	$4000	print_int()
00001040	JUMP	-32	Top of loop

Classifying Instructions

Print out numbers 1-10

Address	Instruction		Type
00001000	MOV	$1,M[10]	Store
00001004	MOV	$10,M[11]	Store
00001008	MOV	M[10],A	Fetch
00001012	MOV	M[11],B	Fetch
00001016	COMPARE	A,B	ALU
00001020	EQUAL?	$1044	Absolute branch
00001024	PUSH	A	Stack
00001028	ADD	$1,A	ALU
00001032	MOV	A,M[10]	Store
00001036	CALL	$4000	Absolute branch
00001040	JUMP	-32	Relative branch

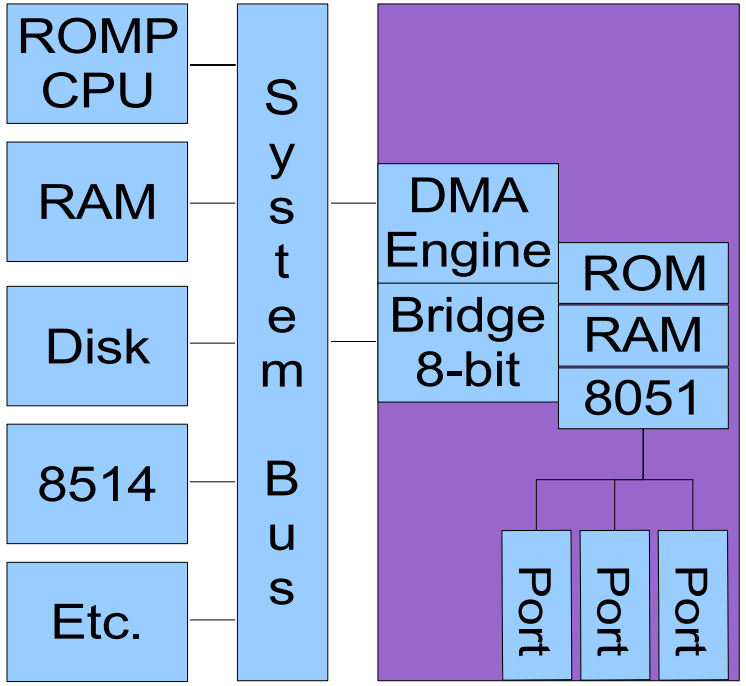
“Reserved (Set to Zero)”

The Scene

- Mid-1980's
- IBM “RT PC”
- “Multiprotocol adaptor”
  - Intel 8051
  - Some Intel bus bridge
  - DMA engine
  - RS-232/422 ports
  - Some bizarre dial port

Key features

- Narrow Intel bus bridge
- Protocol code loaded from host device driver
- Boot loader in ROM



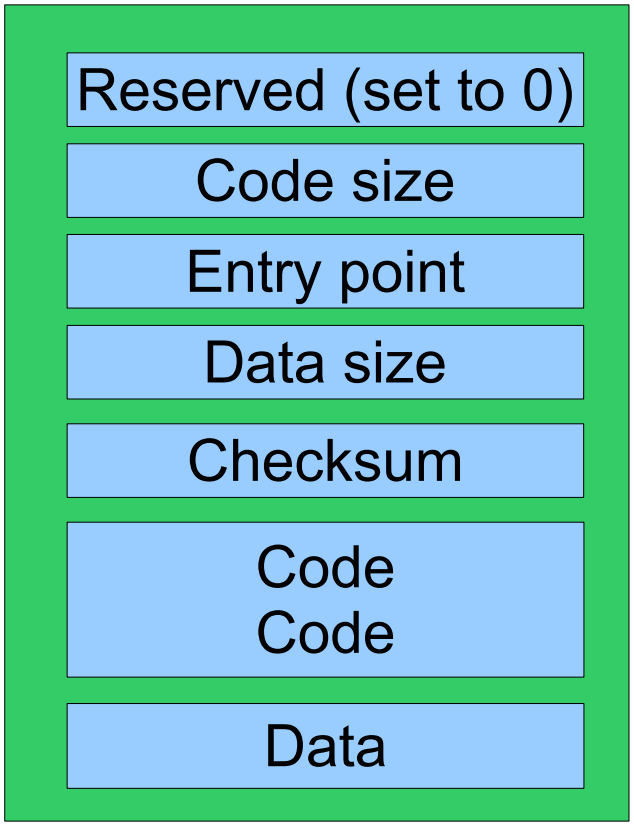
“Reserved (Set to Zero)”

Microcode

- Intel 8051 binary
- Commanded by host to transfer data across bus to/from RAM
- Able to code/decode packet data onto/from wire
- Card could implement checksum and retransmission

File format

- Code size
- Entry point
- ...



The Fun Begins

First program

- Send 1-byte constant to host port (generates interrupt)
- Enter infinite loop
- ⇒ Works!

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Enter infinite loop

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Second program

Program port #0 to be RS-232, no modem control, 9600 bps

Transfer packet from host via DMA

```
while (ptr < end)
  while (!IDLE(0))
    continue;
  output(*ptr++);
```

⇒ Hangs silently!

Houston, We Have A Problem

Inquiry is hard

- No way to inspect card – RAM, registers, etc.
  - *Everything* is under control of boot loader or downloaded code
    - » Code wedges ⇒ no more data
- Only two forms of communication possible
  - 8-bit code sent by bridge with host interrupt
    - » Simple enough: out(port, val)
    - » Only 8 bits (more like 7)
  - DMA
    - » Can send arbitrary data dumps
    - » Except it doesn't work

#include <laborious_debugging_session.h>

Time Passes...

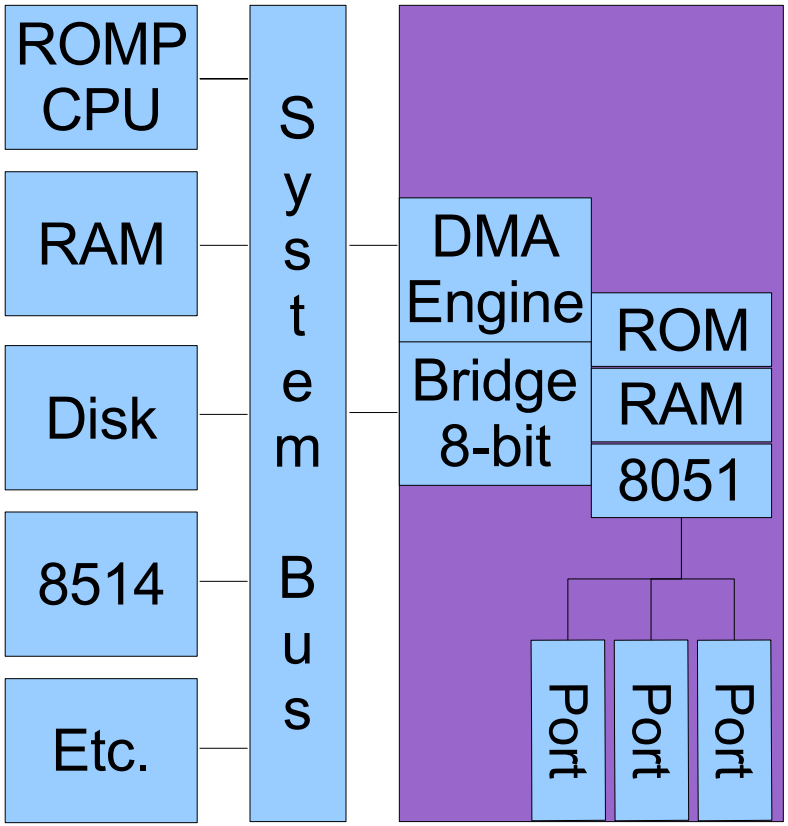
Basic approach

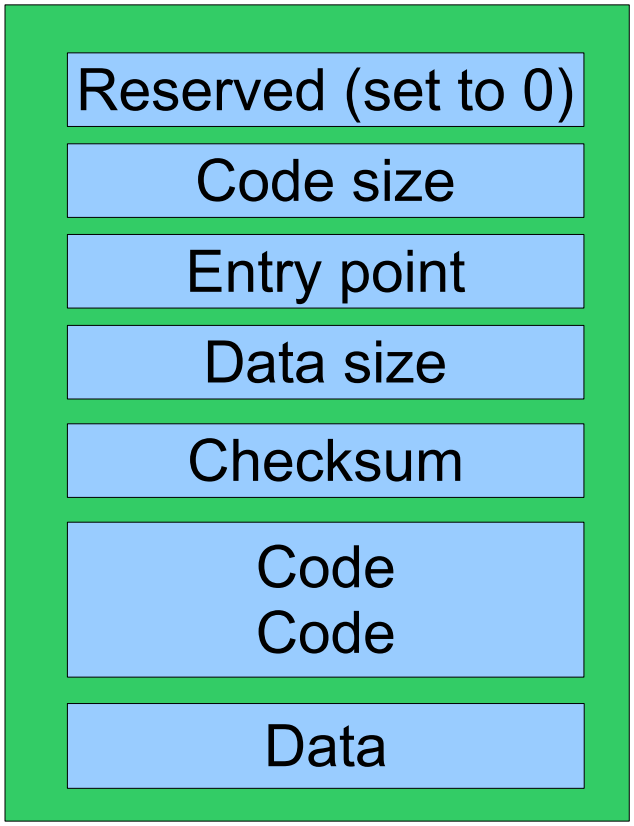
- Write a tiny program
- Download it
- See what tiny answer it returns (if any)

Results

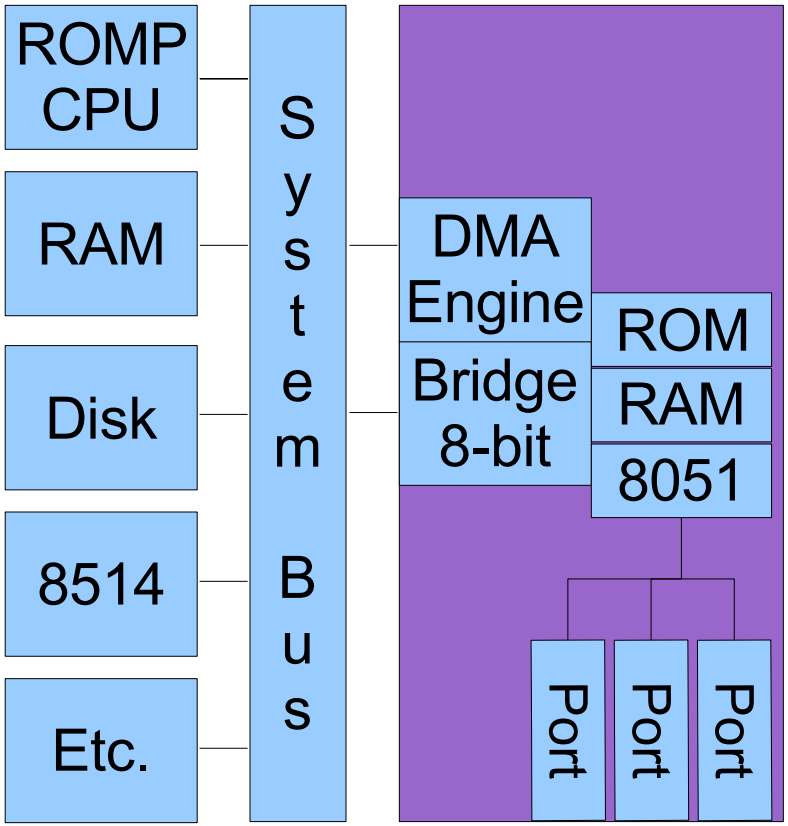
- *Most* 8051 instructions appear to work
  - Port input/port output (thankfully!)
  - Arithmetic, shift/roll
  - RAM load/store
  - Relative branch
- Some instructions don't work so well
  - Call/return
  - Jump (absolute branch)
- ??? (????)

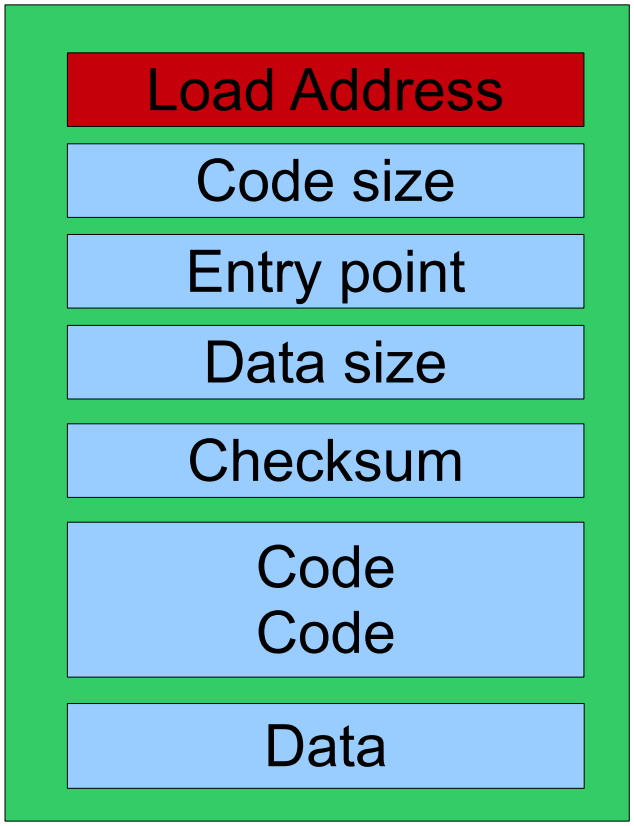
Food for Thought?





“Reserved (Set to Zero)”!!!!!





Residual Amusement

Contacting the developers inside IBM

- Very hard
  - Intentionally very hard
- Insistence
  - That's not how it works!
  - The documentation is correct!
  - We know how our product works!

Residual Amusement

Contacting the developers inside IBM

- Very hard
  - Intentionally very hard
- Insistence
  - That's not how it works!
  - The documentation is correct!
  - We know how our product works!
- Further insistence
  - “Steve” no longer works in the group
    - » After some time, his notes turn up
    - » “It appears that the development version did that”
    - » “No card with that behavior ever shipped to customers”

Lessons?

Is this just a horror story?

- Are there lessons?

Observations

- The problem wasn't “in the code”
  - All programs downloaded to the card were correct
    - » Well, most
  - The boot loader was also correct
  - But the execution environment was (subtly) wrong
    - » printf()/gdb approach would address situation only diffusely
    - » ...if available (not even close!)

What is debugging really?

Debugging

Two stories

- Plan: Hopes and dreams for the future of humanity
- Observation: Tale of woe

Key observation

- They are mostly the same story!
  - The beginnings are *identical*
  - Somewhere there is a tiny discrepancy
  - The stories continue “in a similar vein” after the divergence
  - One story ends in disaster

Debugging

How to progress?

- A *deep* understanding of the stories is necessary
  - Branch vs. Jump!
  - All abstractions are gone at that point
- Measuring which parts happen correctly is *not easy*
  - May require embedding test code in application
  - May require writing entire test applications

This looks like science!

- Hypothesis
- Experimental design
- Measurement
- Analysis

Debugging Suggestions

Move beyond "plot summaries"

- "My program dies"
- "My program dies with a segmentation fault"
- "My program dies with a segmentation fault in xxx()"
  - That one is getting *closer*, but...

Deepen your level of detail

- What was your story of hope, in detail?
- What parts of your story *already happened*?

Measurement Techniques

"Obvious"

- printf()
- single-step the program

Moving beyond the obvious

- Know your debugger
  - breakpoints, watchpoints
- Those pesky registers (in assembly code)
  - The values should always make sense – all of them

Writing code

- Breakage of a complex data structure is, well complex
- Probably need code to check invariants
  - Doing it by hand is fun at most once

Record-Keeping

While you're working

- Keep a “bug diary”
  - What you've tried
  - What you've learned
  - What you don't know how to measure
  - What results are confusing
  - What to try next

After you find the bug

- Keep a “bug diary”
  - Last week I found an xxx bug
  - This week I found an xxx bug
  - Maybe I should check for xxx bugs when I run into trouble
- This is part of the “Personal Software Process” (PSP)

Asking for Help

- **"Plot summary" is not enough**
  - We probaby have no idea what's wrong
    - Really!
- **You should always have a measurement plan**
  - What is the next thing to measure?
  - How would I measure it?
- **You may reach the end of your rope**
  - Some things are genuinely tricky to debug
    - This is a good learning experience

Asking for Help

When are you ready to ask for help?

- You have a long, detailed story – this is *critical!!!*
  - "Story" often needs one or two pictures
- Parts of the story are clearly happening
  - You have straightforward evidence, you are confident
- You have a measurement problem
  - Too many things to measure?
  - No idea how to measure one complicated thing?
  - Measurement results "make no sense"?

Summary

Debugging is about reconciling two stories

- **“Plot summaries” aren't stories (you must zoom in)**
- **“If you don't know where you are going, you will wind up somewhere else.” — Yogi Berra**

Measure multiple things, use multiple mechanisms

You should “always” have a next measurement target

When you ask for help, bring a long story

- **...which you will naturally be an expert on the first part of**