Norwegian University of Science and Technology

Compiler Construction

Lecture 1: Motivation and History

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whoami?

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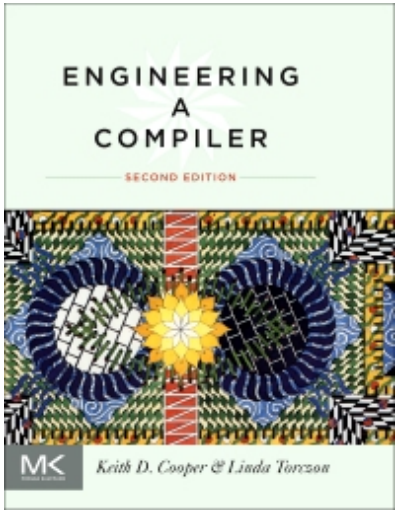
- Studied computer engineering and applied mathematics (Univ. Siegen)
- PhD (Univ. Marburg) 2005
- Assist. Prof. TU Dortmund 2007–14
- Leeds Beckett U., Oracle Labs UK 2014–16
- Assoc. Prof. Coburg Univ. 2016–19
- Assoc. Prof. NTNU 2020–…

- Research Interests

  Compilers, operating systems, parallelization, dependability, embedded systems

Literature

Authors	Keith Cooper, Linda Torczon
Title	Engineering a Compiler (Second Edition)
ISBN	9780120884780 (hardcover) 9780080916613 (ebook)



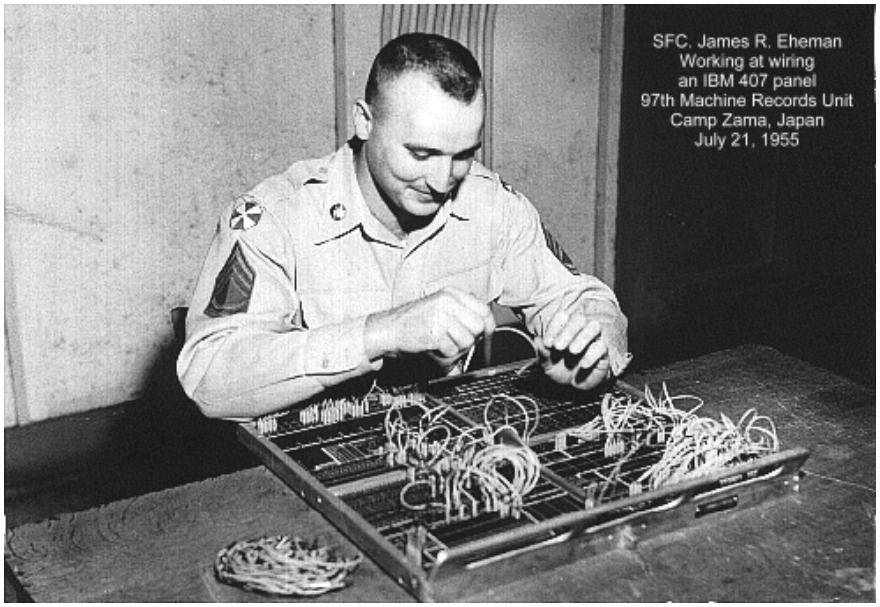
+ additional papers, articles, … on my web page: http://folk.ntnu.no/michaeng/

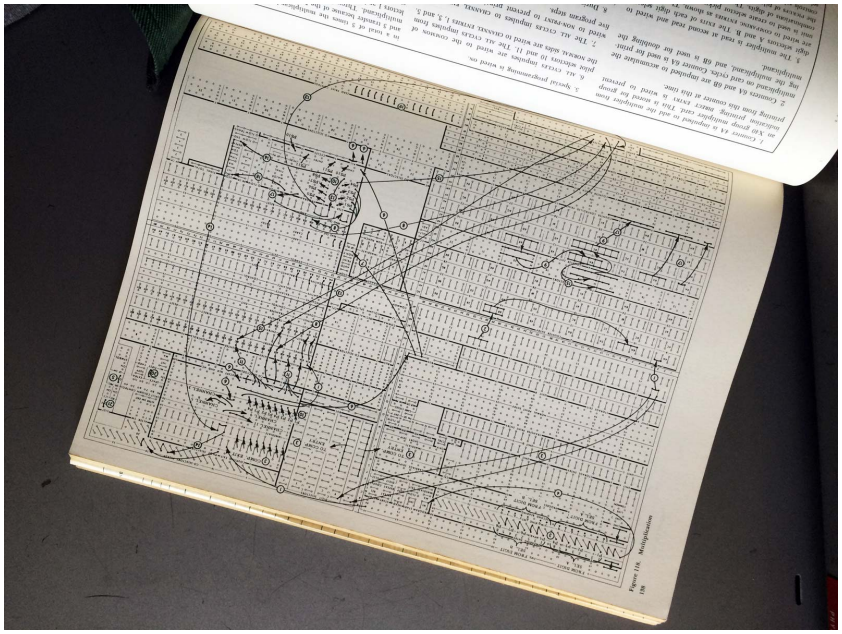
Overview

- History: the evolution of programming
  - from plugboards to compilers
- History of compilers
- The compilation process
- Semester overview

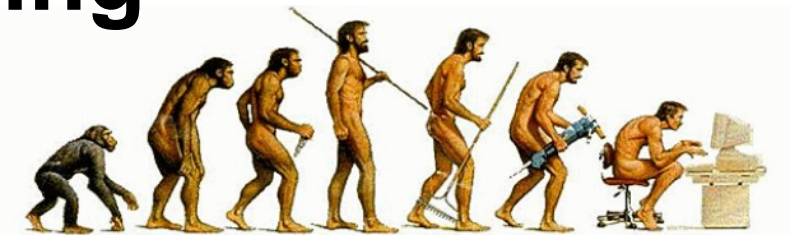
Evolution of programming

- Early "computers" were electric calculating machines
- "Programming" meant creating a machine configuration using a plugboard
  - Bugs/changes => rewire...

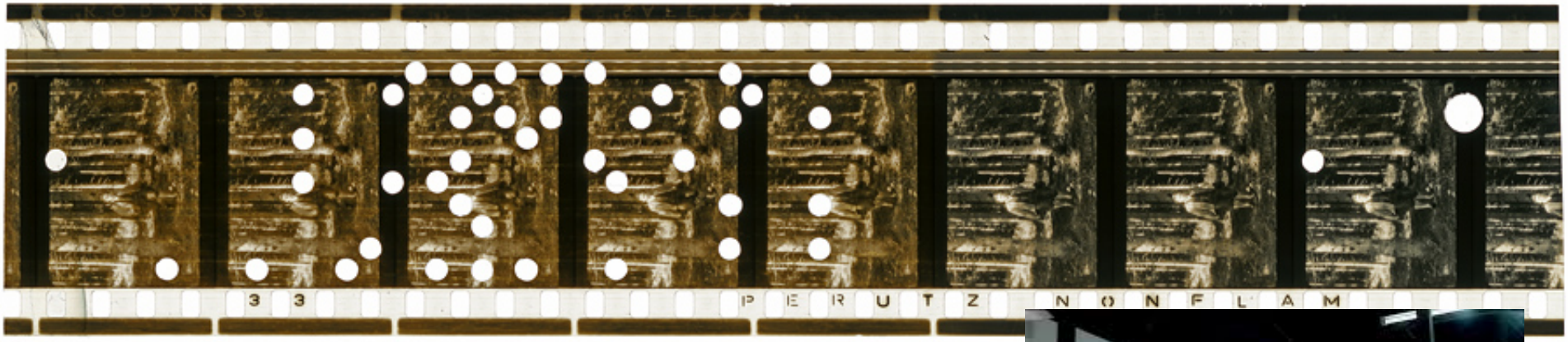




Evolution of programming



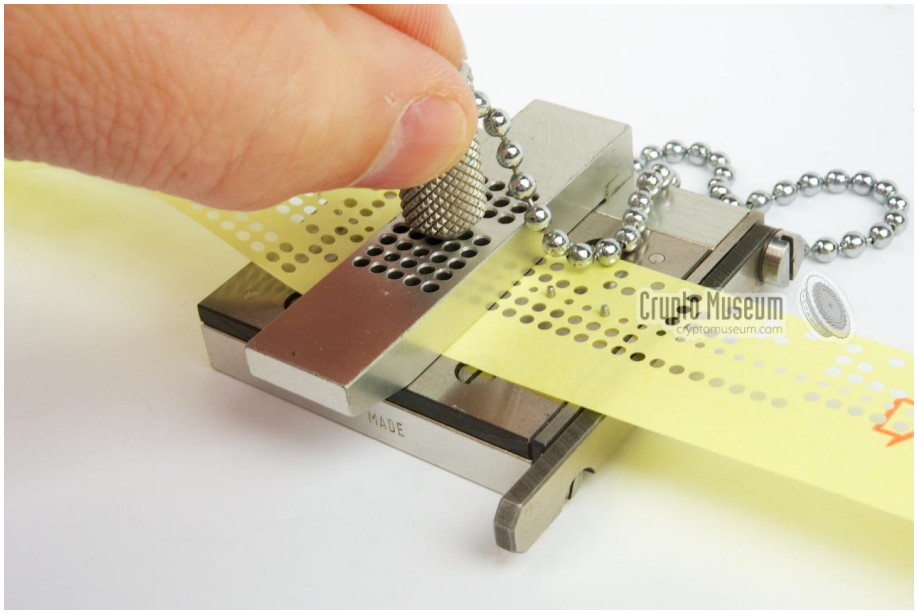
- Early programmable computers: “make bits by hand”
  - Zuse Z3 punched tape (1943): holes stamped in old cinema film rolls
  - later: paper tape



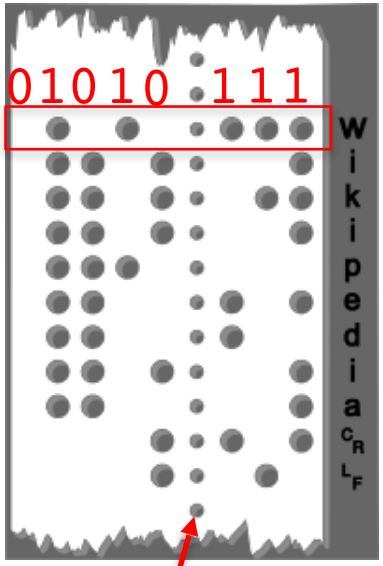
  - One word (set of bits) encoded per column
  - “hole” = log. 1, “no hole” = 0
  - e.g. 8 bits (one byte) per column

What's on the tape?

- "…it depends"
- Data (text, numbers, …)
  - e.g. ASCII characters: 01010111 = 0x57 = "W"
- but also instructions



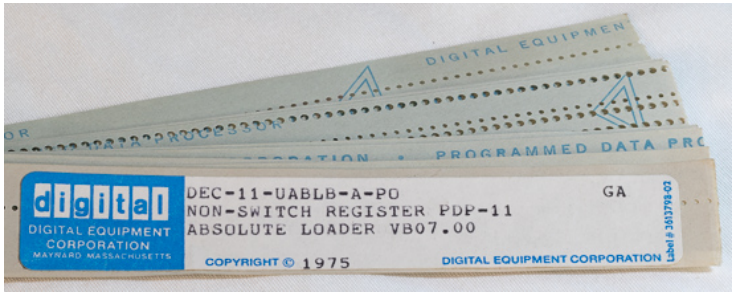
Manual tape punch

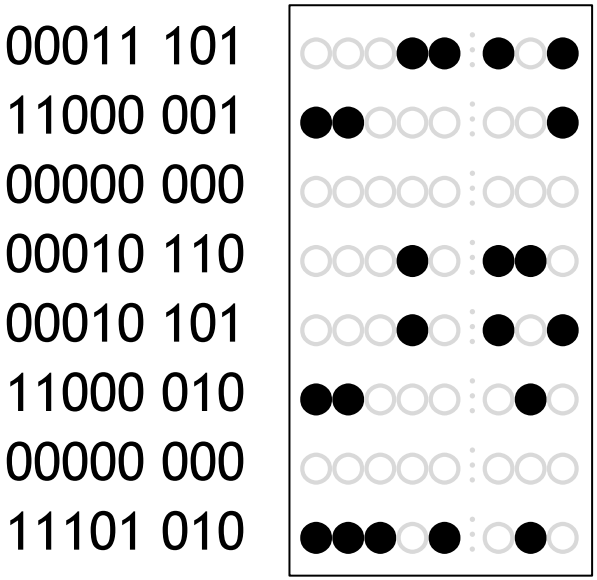


transport holes
(don't encode data)

Instructions on tape

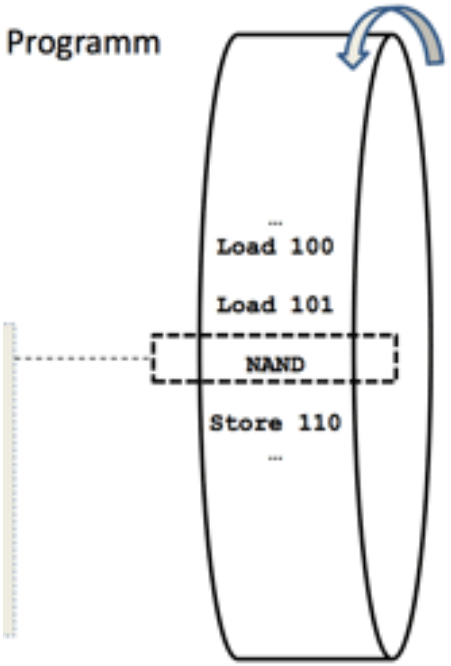
- Early computers (like the Z3) had no program storage
- The computer reads one instruction after the other from tape
- Later: load program from tape into memory
- Example: part of DEC PDP-11 boot loader on paper tape (1975)





Building program structures

- Machine instruction on paper tape
- Columns (e.g. bytes) read one after the other
  - PDP-11 puts bytes into consecutive memory locations
  - Z3 reads **and executes** instructions from tape one after the other



- How can sequences of instructions be repeated?
  - Simply tape the end of the paper tape to the start: create a **loop**
- How could one implement conditional execution of code (if/then/else)?

A manually created loop

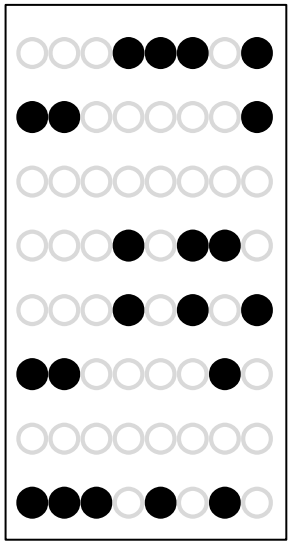
Programs in memory

- Running code from paper tape is inconvenient
- John von Neumann invented the stored program concept (late 1940s)
  - Code and data share the same memory
- Until the 1970s, computers had **front panels** with switches and lights that enabled the operator to view and change every bit in the system
- Without boot ROM: boot loader had to be “toggled” in by hand…

DEC PDP11/70 front panel replica (3D printed) connected to a Raspberry Pi running a PDP11 emulator

Programs in memory

- PDP11 instruction words are always multiples of 16 bits

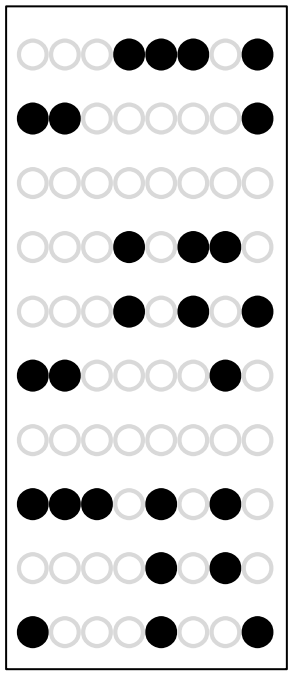


	octal	binary (16 bit word)
00011101 11000001	**016701**	= 0 001 110 111 000 001
00000000 00010110	**000026**	= 0 000 000 000 010 110
00010101 11000010	**012702**	= 0 001 010 111 000 010
00000000 11101010	**000352**	= 0 000 000 011 101 010

- Would you want to program a computer this way?

From machine code to assembly

- Assembler: human readable machine instructions
- Common: 1:1-equivalence of assembler instruction to binary machine instruction
  - Some assemblers use “pseudo instructions” (ARM, MIPS, RISC-V)



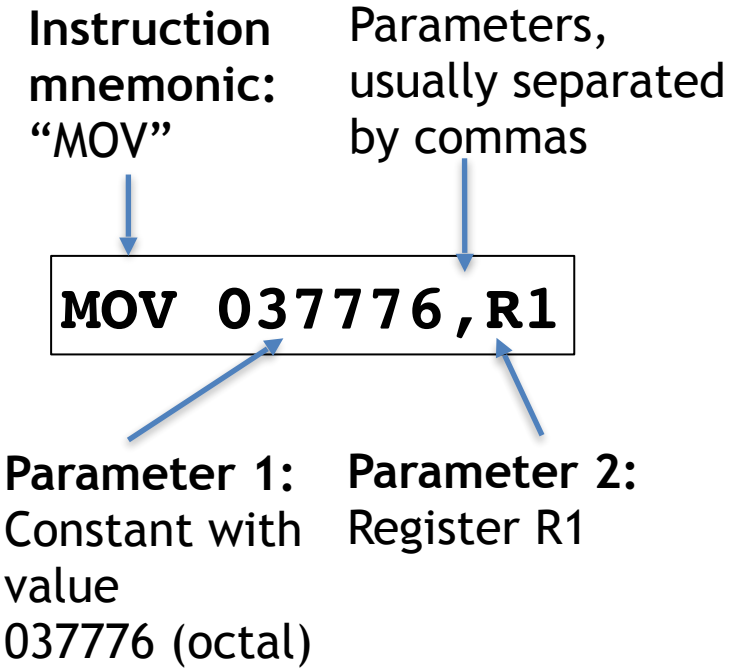
octal encoding of machine instr. | **equivalent assembler instruction**

```
016701 000026   MOV 037776,R1
012702 000352   MOV #352,R2
005211          INC @R1
```

From binary to assembler

- Assembler instructions consist of instruction name (*mnemonic*) and optional parameters
- Parameters can be constants, register numbers, addresses

octal encoding of machine instr.	assembler instruction with numeric constants
016701 000026	MOV 037776,R1
012702 000352	MOV #352,R2
005211	INC @R1
105711	TSTB @R1
100376	BPL 037756
116162 000002	
037400	MOVB 2(R1),37400(R2)
005267 177756	INC 037752
000765	BR 037750
177550	.WORD 177550



Making assembler (better) readable

- Using “magic numbers” is still quite inconvenient
- Most assemblers support the use of **symbolic names** for constants and memory addresses (“**labels**”)
- In addition, comments are supported (and ignored 😉)

memory address	**machine instr.**	**assembler instr. using numbers**
037744:	016701 000026	MOV 037776,R1
037750:	012702 000352	MOV #352,R2
037754:	005211	INC @R1
037756:	105711	TSTB @R1
037760:	100376	BPL 037756
037762:	116162 000002	
	037400	MOVB 2(R1),37400(R2)
037770:	005267 177756	INC 037752
037774:	000765	BR 037750
037776:	177550	.WORD 177550

labels **symbolic name**

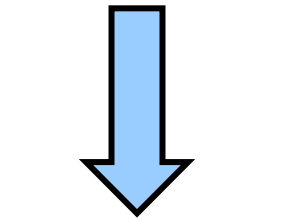
```
        mov device,r1@   // get csr address
loop:   mov #352,r2      // get offset
offset: inc (r1)         // read frame
wait:   tstb (r1)        // wait for ready
        bpl wait

        movb 2(r1),bnk(r2)  // store data
        inc loop+2          // bump address
        br loop
device: HSR      // csr, or 177560 for teletype
```

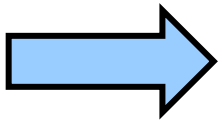
From assembler to high-level languages

- Assembler helps (humans) to read machine-language programs
- What's missing compared to higher-level languages?
  - Constructs to enable program structure:
    loops (for, while, do) and **conditions** (if, switch)
  - **Variables**
    - Labels and symbolic names in assembler are just direct aliases for memory addresses resp. constants
  - **Data types, structures and objects**
    - Assembler only knows about machine data types
  - **Functions/methods**
    - Declaring, passing and returning of parameters
  - **Classes and objects**…
- **Compilers** can translate these constructs to machine language

The compilation process black box

```
int main()
{
   . . .
   sum = num1 + num2;
   . . .
}
```





```
. . .
0xE59F1010
0xE59F0008
0xE0815000
0xE59F5008
. . .
```

Example: from C to assembler

C program: convert upper case to lower case letters

- implemented as C function

```
char tolower(char c)
{
  if (c >= 'A' && c <= 'Z')
     c += 'a' - 'A';

  return c;
}
```

- Uses ASCII character encoding:
  - ‘A’ = 0x41, ‘B’ = 0x42, ...
    ‘a’ = 0x61, ‘b’ = 0x62, …

- If character in c is an upper case letter (c in [‘A’, ‘B’, … ‘Z’]), then the code adds the difference between lower case ‘a' and upper case ‘A’ to variable c
- otherwise, c is returned unchanged

	0	1	2	3	4	5	6	7
0	NUL	DLE	space	0	@	P	`	p
1	SOH	DC1 XON	!	1	A	Q	a	q
2	STX	DC2	"	2	B	R	b	r
3	ETX	DC3 XOFF	#	3	C	S	c	s
4	EOT	DC4	$	4	D	T	d	t
5	ENQ	NAK	%	5	E	U	e	u
6	ACK	SYN	&	6	F	V	f	v
7	BEL	ETB	'	7	G	W	g	w
8	BS	CAN	(	8	H	X	h	x
9	HT	EM	)	9	I	Y	i	y
A	LF	SUB	*	:	J	Z	j	z
B	VT	ESC	+	;	K	[	k	{
C	FF	FS	,	<	L	\	l	|
D	CR	GS	-	=	M	]	m	}
E	SO	RS	.	>	N	^	n	~
F	SI	US	/	?	O	_	o	del

C to assembler: control structures

Simplification of the C program

- Assembler does not support complex “if” instructions
  - Only comparison of values and conditional jumps
- Compiler changes “and” (&&) operator into consecutive “if”s
  - Shown as simplified C code
- Complex expressions (“c += …”) are also broken down
  - Three address code (two operands, one result)

```
char tolower(char c)
{
  if (c >= 'A' && c <= 'Z')
     c += 'a' – 'A';

  return c;
}
```

```
char tolower(char c)
{
  char temp;

  if (c >= 'A') {
    if (c <= 'Z') {
      temp = 'a';
      temp = temp – 'A';
      c = c + temp;
    }
  }

  return c;
}
```

C to assembler transformation

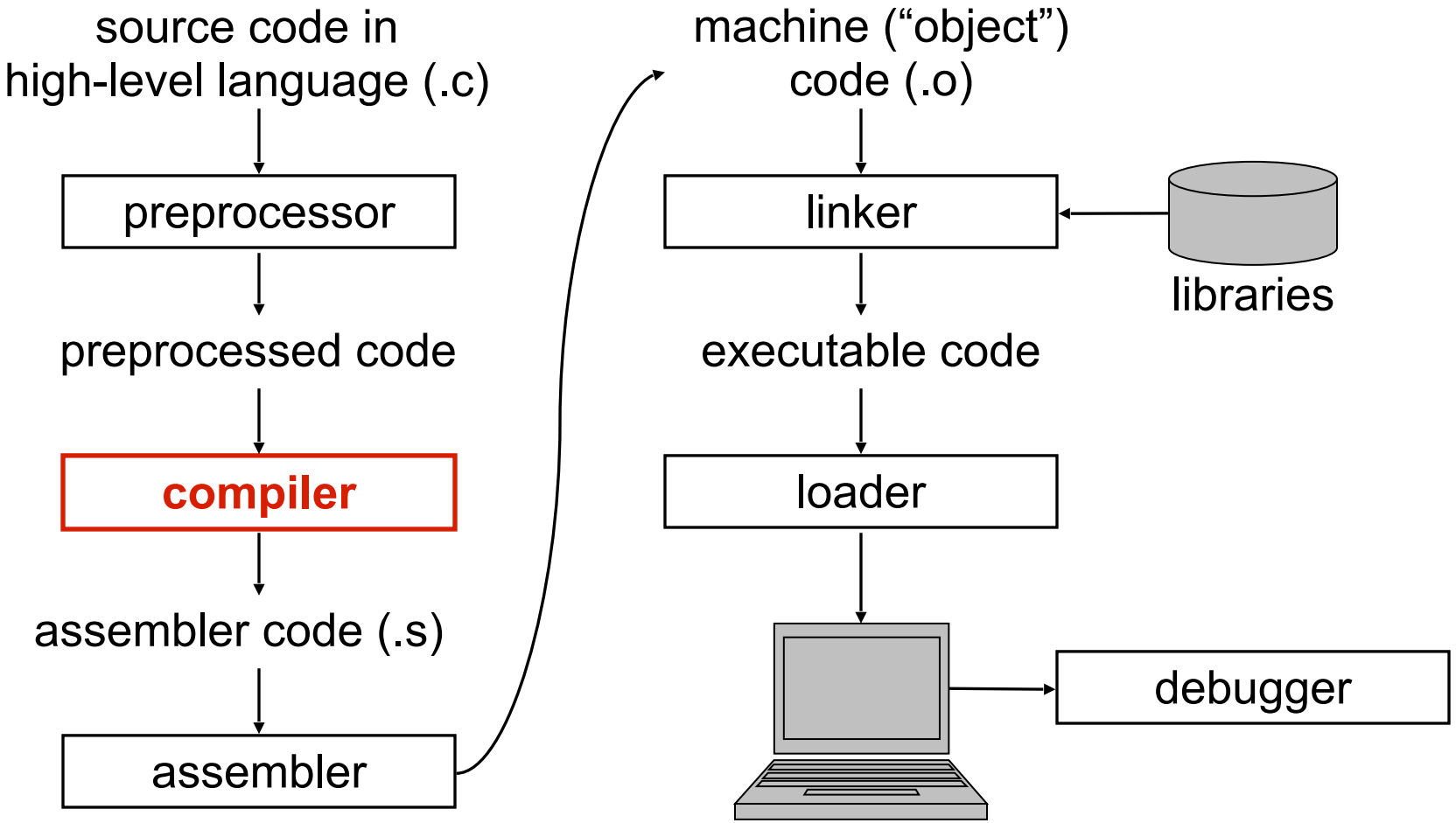
Convert simplified C program to ARM (Thumb) assembler

- No variables in assembler: variables in C assigned to processor registers
- c = r0, temp = r1

```
char tolower(char c)
{
  char temp;

  if (c >= 'A') {
    if (c <= 'Z') {
      temp = 'a';
      temp = temp – 'A';
      c = c + temp;
    }
  }
  return c;
}
```

```
    AREA    text, CODE, READONLY

    EXPORT  tolower

tolower
    CMP     r0, #0x41
    BLT     lowerCase
    CMP     r0, #0x5a
    BGT     lowerCase
    MOV     r1, #0x61
    SUB     r1, #0x41
    ADD     r0, #r1
lowerCase
    BX      lr

    END
```

Compilation process in detail



Transpilers and other fun things

- Compilers do not always transform high-level languages to low-level machine code
- Source-to-source-compiler ("transpiler")
  - C-to-C, f2c (Fortran to C)
  - emscripten: C/C++ to Javascript
- Static binary transformation [3]
  - Dynamo optimization
- Just-in-time (JIT) compilation
  - Java VM, Android Dalvik/ART JIT
  - Transmeta Crusoe

Example: emscripten

- Source-to-source compiler [1]
  - Can transform languages with LLVM compiler frontend (C, C++, ...)
  - Runs as LLVM back end, produces JavaScript subset (wasm)
- Example use case: run Doom / Quake (written in C) in browser

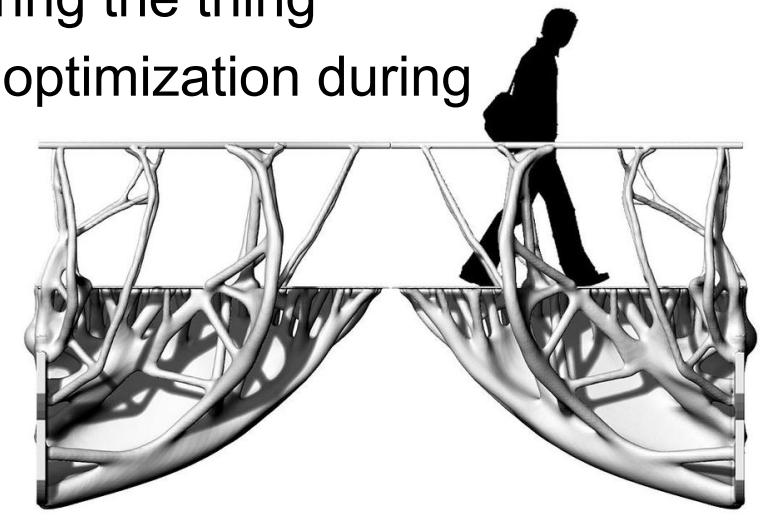
```
#include <stdio.h>
int main() {
  float fact = 1.0;
  int c;
  for (c=1; c<13; ++c) {
      fact *= c;
  }
  printf("%f\n", fact);
}
```

⇒ Emscripten ⇒

```
(loop $label$2
 (block $label$3
  (local.set $4
   (local.get $3)
  )
  (local.set $5
   (i32.lt_s
    (local.get $4)
    (i32.const 13)
   )
  )
  (if
   (i32.eqz
    (local.get $5)
   )
   (br $label$3)
  ...
```

A different view of code

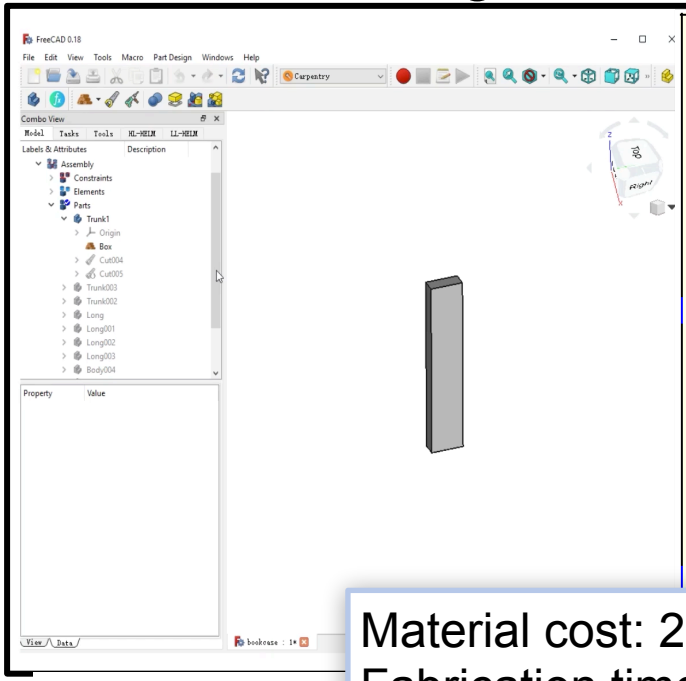
- Compilers can also be used in *very* different domains [5]
- Current research: "matter compiler"
  - Map high-level description (design) of a physical thing to instructions for machines manufacturing the thing
  - Check impossible requirements and optimization during compilation
- Example: 3D printing [5]
  - Compiler-generated 3D-printed bridge [6]
  - Output: "G code" to control 3D printer




```
T1 M6
G90 G94
G54 X0 Y0
G00 X0 Y0
G00 X0 Y-100
G01 X-59 Y81 F200 M3
G01 X95 Y-31
G01 X-95 Y-31
G01 X59 Y81
G01 X0 Y-100
G02 X100 Y0 I0 J100
G02 X0 Y-100 I-100 J0
M30;
```

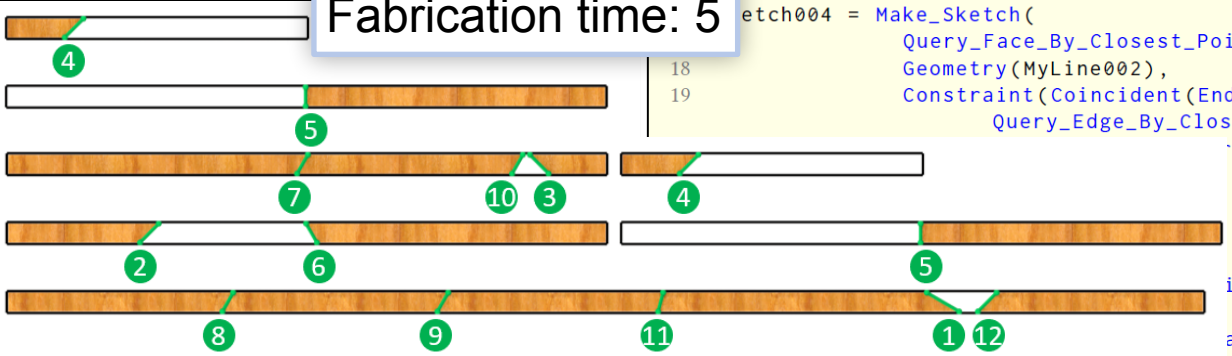
Example: carpentry compiler

- Convert design of thing as 3D view to manufacturing code [4]




```
Box001 = Make_Stock(457.2, 38.1, 88.9);
MyLine000 = Line(457.2, 0, 435.203, 38.1);
Sketch = Make_Sketch(
            Query_Face_By_Closest_Point(Box001, 228.6, 19.05, 88.9),
            Geometry(MyLine000),
            Constraint(Coincident(Start(MyLine000), End(
                  Query_Edge_By_Closest_Point(Box001, 228.6, 0, 88.9))),
                  PointOnObject(End(MyLine000), Query_Edge_By_Closest_Point(
                  Box001, 228.6, 38.1, 88.9)), Angle(Start(
                  Query_Edge_By_Closest_Point(Box001, 457.2, 19.05, 88.9)), Start
                  (MyLine000), 30)));
Cut = Make_Cut(Box001, Sketch, 0);
MyLine001 = Line(0, 38.1, 21.997, 0);
Sketch001 = Make_Sketch(
               Query_Face_By_Closest_Point(Cut, 228.6, 19.05, 88.9),
               Geometry(MyLine001),
               Constraint(Coincident(Start(MyLine001), End(
                     Query_Edge_By_Closest_Point(Cut, 0, 19.05, 88.9))),
                     PointOnObject(End(MyLine001), Query_Edge_By_Closest_Point(
                     Cut, 228.6, 0, 88.9)), Angle(End(Query_Edge_By_Closest_Point
                     (Cut, 0, 19.05, 88.9)), Start(MyLine001), 30)));
t001 = Make_Cut(Cut, Sketch001, 1);
x = Make_Stock(457.2, 38.1, 88.9);
Line002 = Line(435.203, 38.1, 457.2, 0);
etch004 = Make_Sketch(
               Query_Face_By_Closest_Point(Box, 228.6, 19.05, 88.9),
               Geometry(MyLine002),
               Constraint(Coincident(End(MyLine002), End(
                     Query_Edge_By_Closest_Point(Box, 228.6, 0, 88.9))),
                     t(MyLine002), Query_Edge_By_Closest_Point(
                     88.9)), Angle(MyLine002, -60)));
int(Cut004, 228.6, 19.05, 88.9),
art(MyLine003), End(
                     Query_Edge_By_Closest_Point(Cut004, 0, 19.05, 88.9))),
                     PointOnObject(End(MyLine003), Query_Edge_By_Closest_Point(
                     Cut004, 228.6, 0, 88.9)), Angle(End(
                     Query_Edge_By_Closest_Point(Cut004, 0, 19.05, 88.9)), Start(
```

Material cost: 2.95
Fabrication time: 5



Semester overview (tentative)

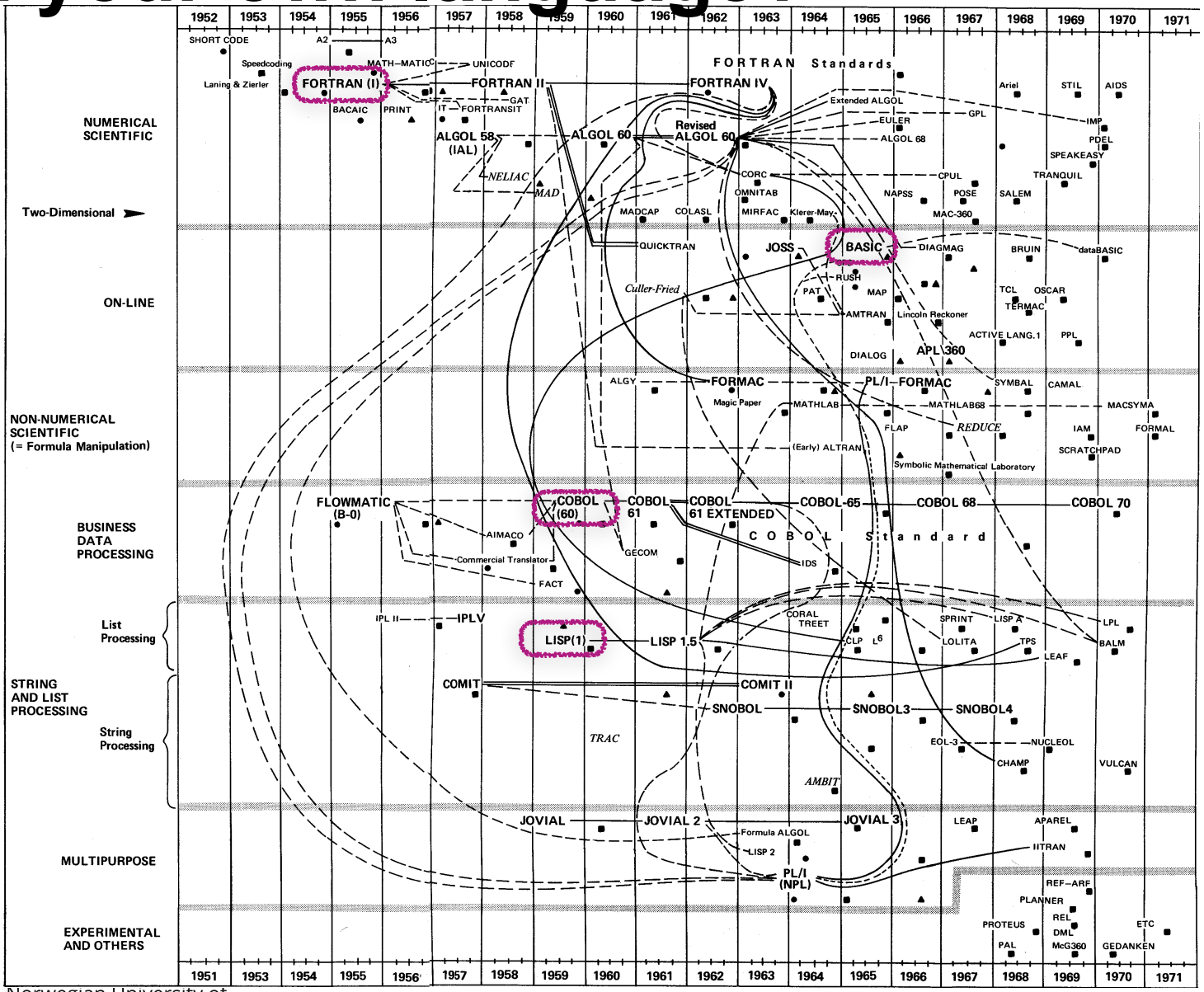
- Structure of a typical compiler
- Frontend
  - Scanning
  - Parsing and grammars
- Intermediate representations
  - Abstract syntax trees (ASTs) and SSA form
- Backend
  - Code generation
  - Code optimization
  - Linking
- Static code analysis

Design your own language?

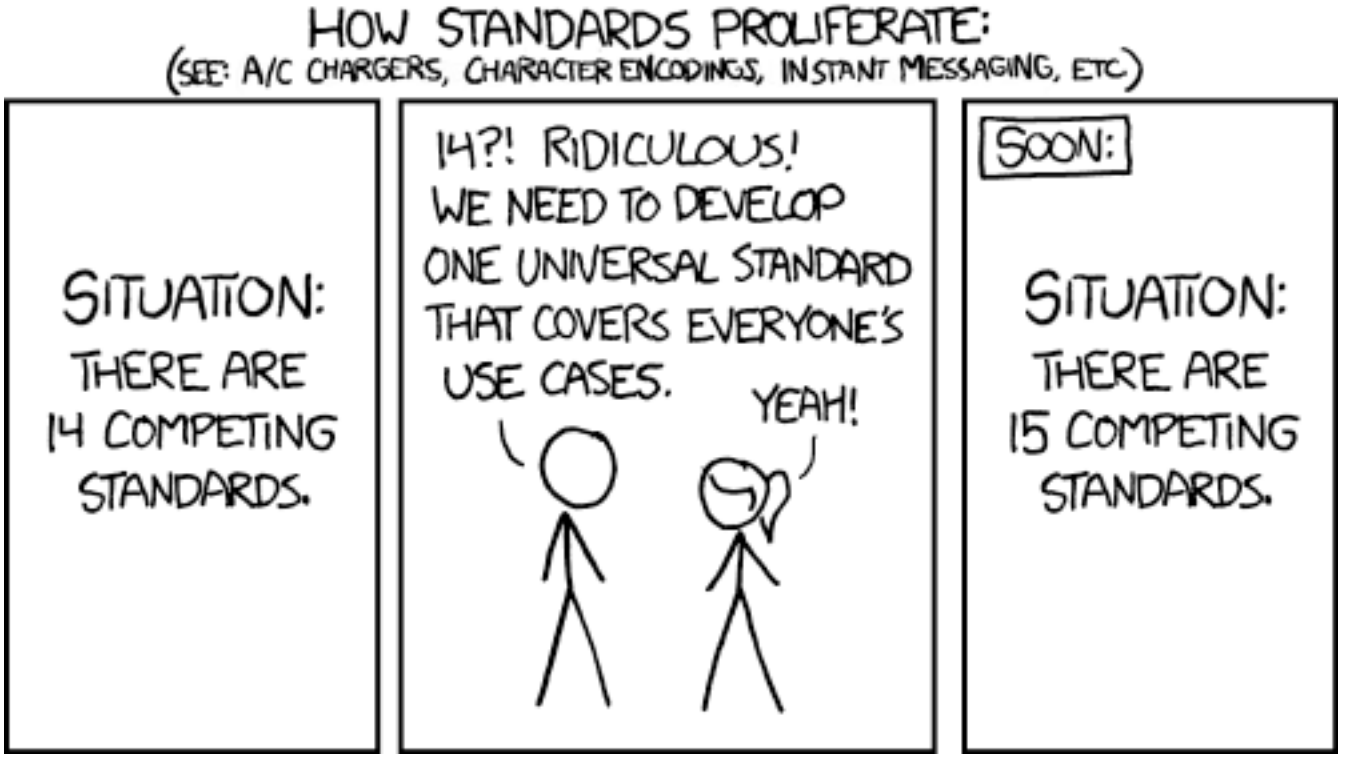
20 years of development [2]

Which languages are still widely used?

- FORTRAN
- COBOL
- LISP
- BASIC



Design your own language?



References

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6. **"3D Printing And The Complexity Of Compiling Matter"** https://www.forbes.com/sites/valleyvoices/2015/09/02/3d-printing-and-the-complexity-of-compiling-matter/