CEN G444:
Language Processors
(aka. Compilers)

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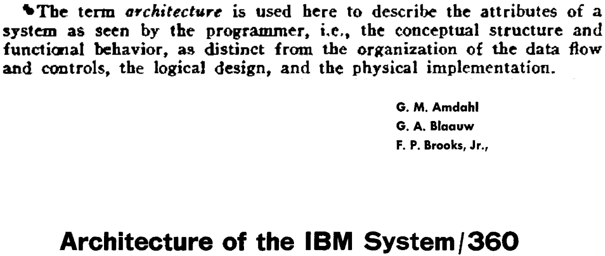
Fundamental questions in programming

- The scientific question: What is universal computation? How can we represent it?
- The black art of PL design question: What makes a programming language captivate programmers?
- The methodological question: Are there principled ways to represent universal computation for any computer?
- The engineering question: How can arbitrarily complex and potentially unlimited universal computation be mapped to a computer with finite means?
- The philosophical question: Is computer science the practice of the extended-human, or extended-practice of the human?

- Programmers see the computer through the window provided by the designers at the level of its functional architecture.
- This window is provided by you, the designer.



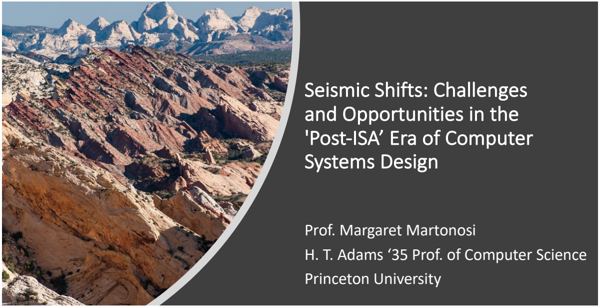
*The term *architecture* is used here to describe the attributes of a system as seen by the programmer, i.e., the conceptual structure and functional behavior, as distinct from the organization of the data flow and controls, the logical design, and the physical implementation.

G. M. Amdahl
G. A. Blaauw
F. P. Brooks, Jr.,

Architecture of the IBM System/360

Amdahl et al. (1964) First use of the term 'computer architecture'

A more recent computer architect gave the following talk to ACM Martonosi (2022).



Seismic Shifts: Challenges and Opportunities in the 'Post-ISA’ Era of Computer Systems Design

Prof. Margaret Martonosi

H. T. Adams ‘35 Prof. of Computer Science

Princeton University

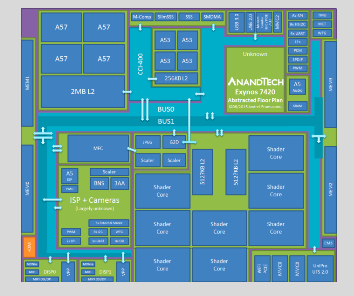
2022: We are here

Massive Heterogeneity:

- Dozens of ISAs on chip + Accelerators
- Memory, Data Heterogeneity
- Memory Consistency Models

Systems heterogeneity too:

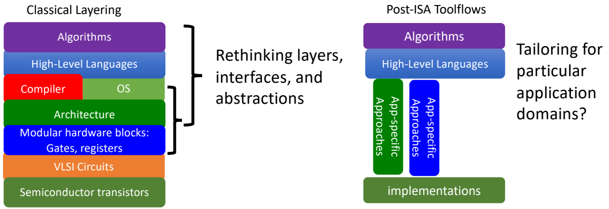
- Thousands of distinct Android, IoT devices…



ANANDTECH Exynos 7420 Abstracted Floor Plan ©06/2015 Andrei Frumusanu

Martonosi

End-of-Moore Systems: Rethinking Full-Stack Approaches



Rethinking layers, interfaces, and abstractions

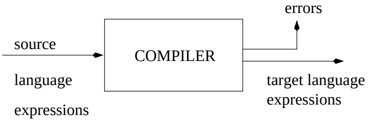
Tailoring for particular application domains?

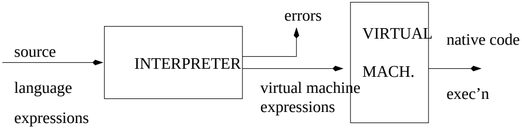
Martonosi

One way or the other, we need to provide a means to implement ideas about computation in finite capabilities of a physical computer.

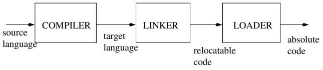
- Language processing (compiling/interpretation/translation) brings together
  - Computer Architecture,
  - OS,
  - Formal Languages and Automata Theory,
  - Software Engineering
  - and Programming Languages.
  - And, as of lately, philosophy of computer science, such as Bozșahin (2018).

- Any computation via programming can be visualized as the following process:

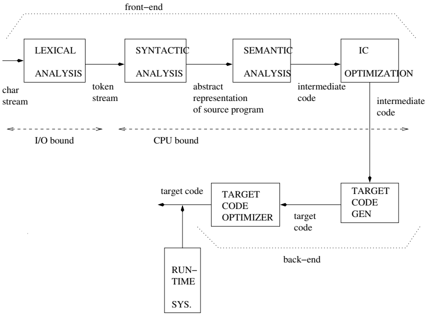




- Some virtual machines: SAM: Stack Machine, Java Virtual Machine (JVM); FAM: Functional Abstract Machine; WAM: Warren's Abstract Machine, LLVM: Low-level Virtual Machine



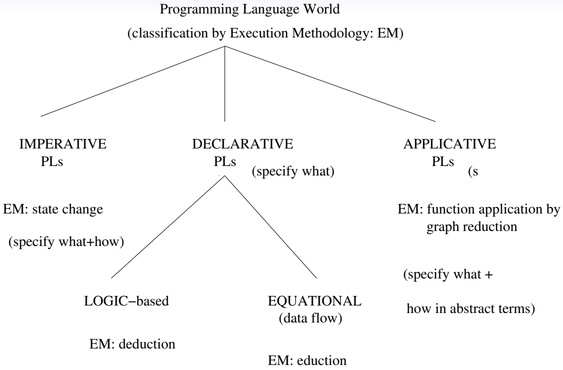
USE OF COMPILERS IN AN ENVIRONMENT



INSIDE THE BLACK BOX

- Need for modularization: Portability, extendibility.

  In many cases the stages are combined (single vs. multi-pass compilers)



- We will study compilers for imperative languages
- Different paradigms call for different compiler design; choice of intermediate code, compiling vs. interpretation; VM-based interpretation.

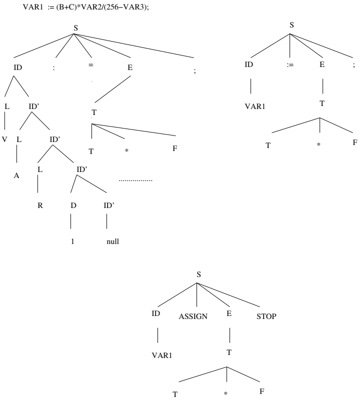
A Walk Through The Stages of Compilation

- XP: A language for arithmetic expressions

$$
\begin{array}{ll}
\text{S} \rightarrow & \text{ID} := \text{E;} \\
\text{E} \rightarrow & \text{E - T} \mid \text{E + T} \mid \text{T} \\
\text{T} \rightarrow & \text{T * F} \mid \text{T / F} \mid \text{F} \\
\text{F} \rightarrow & \text{ID} \mid \text{NUM} \mid \text{(E)} \\
\text{ID} \rightarrow & \text{L ID}' \\
\text{ID}' \rightarrow & (\text{L}\mid \text{D})\ \text{ID}' \mid \varepsilon \\
\text{NUM} \rightarrow & \text{D NUM} \mid \text{D}
\end{array}
$$

STAGE I: LEXICAL ANALYSIS. Tokenize the incoming stream of text.

Why separate lexical and syntactic analysis?



- Separation makes both stages simpler; The parser need not worry about internal structure of tokens, whitespace, comments etc.
- Usually, the grammar of a language is context-free, but the grammar of its tokens is regular. Use more efficient techniques.
- Machine-dependent I/O and alphabetical conventions can be localized.

token types	patterns	lexemes
ID	$L(L\|D)^*$	var1, b, abc5rd
NUM	D^+	256
OP	$(+\|-\|*\|/)$	$+$
ASSIGN	:=	:=

- VAR1 := (B+C)*VAR2 /(256-VAR3);

  ID ASSIGN DEL ID OP ID DEL .....

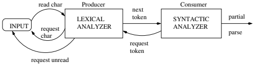
- A by-product of this stage is to start forming a table of meaning-bearing entities, called *the symbol table*.

- Lex analyzer doesn't know anything about the *syntax* of the language; it can fill ST with limited amount of information.

- Symbol table is the most frequently accessed data structure in a compiler (lexical analyzer, parser, type checker, run-time system, optimizer etc.)

  Need efficient insertion and search techniques for ST.

STAGING OF LEXICAL–SYNTACTIC ANALYSES



ex: Fortran IF stmt IF(I,J)=3

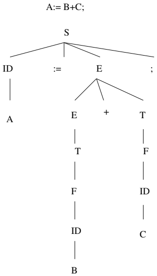
- That's a 2-dimensional array called IF.

  We also have `IF (I.GT.0) ...` and `IF (I(2,4).GT.0.0) ...`

STAGE II: SYNTACTIC ANALYSIS

Assign roles to tokens in parsing; set up symbol table; assign meanings to the use of tokens (syntax-directed translation).

- The meaning (semantics) of a program is what it does (computes).



PARSE TREE for A:=B+C

rule	action
S –> ID := E;	output lvalue ID.name move
ID –> ...	put ID in symbol table
T –> F	T.val <– F.val
E –> E + T	output add
F –> ID	output rvalue ID.name
F –> NUM	output value NUM

- How to get semantic representation from the parse tree: associate semantic actions with rules.
- How do the attributes get instantiated?

  Depends on the parsing strategy.

  in Bottom-up parsing, the attributes are *synthesized* from value of child nodes.

  in top-down parsing, they are *inherited* by children.
- Choice of strategy also affects grammar. XP is left-recursive hence not very suitable for top-down parsing (re-write or use bottom-up).

- RECURSIVE-DESCENT PARSING: a top-down approach

  Write a subprogram for each non-terminal in the grammar

  For terminals, call the lexical analyzer

  Flow of control shows the order of rule application

- ex: rewrite XP as a non-left-recursive grammar.

  ex: $$\begin{array}{ll} S \rightarrow & \text{ID} := E\ ; \\ E \rightarrow & T\ E' \\ E' \rightarrow & +\ TE'\ |\ -\ T\ E'\ |\ \varepsilon \end{array}$$

```
match(T): returns true if next token is of type T

advance(): consumes the lookahead token

procedure S;
begin
   ID;
   if match(ASSIGN) then advance() else error();
   E;
   if match(STOP) then advance() else error();
end;

procedure ID;
begin
   if match(ID) then token:=advance();
   install_id(token);
end;

procedure E;
begin
   T;
   Eprime;
end;

procedure Eprime;
begin
   if match(OP) then {advance(); T; Eprime;}
   else /* no consumption */
end
```

- BOTTOM-UP PARSING: obtain rightmost derivations *in reverse order*.

  An algorithm to pick the right rule in derivations: LR parsing

- XP: A language for arithmetic expressions

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\mathrm{E} \rightarrow & \mathrm{E} - \mathrm{T} \mid \mathrm{E} + \mathrm{T} \mid \mathrm{T} \\
\mathrm{T} \rightarrow & \mathrm{T} * \mathrm{F} \mid \mathrm{T} \,/\, \mathrm{F} \mid \mathrm{F} \\
\mathrm{F} \rightarrow & \mathrm{ID} \mid \mathrm{NUM} \mid (\mathrm{E}) \\
\mathrm{ID} \rightarrow & \mathrm{L}\ \mathrm{ID}' \\
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\mathrm{NUM} \rightarrow & \mathrm{D}\ \mathrm{NUM} \mid \mathrm{D}
\end{array}
$$

```
A:=B+C;
ID:=B+C;
ID:=ID+C;
ID:=F+C;
ID:=T+C;
ID:=E+C;
ID:=E+ID;
ID:=E+F;
ID:=E+T;
ID:=E;
S
```

- STAGE III: SEMANTIC ANALYSIS

ex: type checking

```
A: int;
B: real;

C:= A/B;
```

need to generate code like

```
T:=coerce(A, real);
C:=divide(T,B);
```

- STAGE IV: GENERATING INTERMEDIATE CODE (IC)
- choice of IC depend on source-target language and considerations.

1. Easy to translate into IC (assembly-like for imperative; lambda-calculus like for applicative langs)

2. Easy to obtain from source language (high-level assembler for imperative PLs; stack machines for arithmetic)

3. IC tends to be abstract three-address code (TAC) if RISC is the main target

IC tends to be two-address code if CISC is the main target

Architecture-independent virtual machines

- TAC: result := operand op operand

A:=(B+C-D)/2 translates to TAC

```
t1  :=  B+C;
t2  :=  t1−D;
t3  :=  t2/2;
A   :=  t3;
```

- SAM: A stack machine for XP

  fetch values of IDs from memory to stack (`rvalue x`)

  put values on stack (`push v`)

  put address of ID on stack (`lvalue x`)

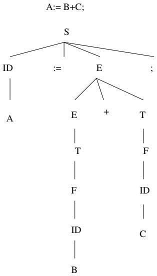
  store in memory (`move`)

  operators

ex: SAM code for A:=B+C-D+10;

```
rvalue B
rvalue C
ADD
rvalue D
SUB
push 10
ADD
lvalue A
move
```

- obtaining the SAM instructions during parsing (as a syntax-directed semantic action)



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- From IC to Target Code (TC)

  Optimizations on IC: combine common subexpresions; eliminate dead code; fix loops; replace some calls with local go to's

  Optimizations on TC: reduce memory fetch; maximize register use

- RISC-V makes us think again about the future of CS
- Freely-developing hardware for freely-developing software

  (I don't mean free hardware or free software. These are all human efforts. Being free *for people* is another matter.)

- Size and energy consumption matter, as well as performance
- Hennessy showed good RISC designs make a difference
- Patterson showed they can be open to custom development publicly: RISC-V
- Together they received the ACM Turing Award in 2017

- It is important for a first course on compilers to go all the way to a physical instruction set.
- Because this may be the only compiler course you take.
- We avoid higher level concepts, such as art and science of error reporting, OOP translation, and closures etc. for this reason.
- At the end I will give a bird's eye view of compiling functional languages.

Amdahl, G. M., G. A. Blaauw, and F. P. Brooks (1964). Architecture of the IBM System/360. *IBM Journal of Research and Development 8*(2), 87–101.

Bozşahin, C. (2018). Computers aren't syntax all the way down or content all the way up. *Minds and Machines 28*(3), 543–567.

Martonosi, M. (2022). Seismic shifts: Challenges and opportunities in the 'post-ISA' era of computer systems design. ACM Techtalks, July.