COS320: Compiling Techniques

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January 30, 2024

Welcome!

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What is a compiler?

- A **compiler** is a program that takes a program written in a *source language* and translates it into a functionally equivalent program in a *target language*.
  - `gcc` : C $\rightarrow$ x86 assembly
  - `javac` : Java $\rightarrow$ Java bytecode
  - `cfront` : C++ $\rightarrow$ C
  - ....

Bjarne Stroustrup's 1983 C++ compiler

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  - ....

- A compiler can also
  - Report errors & potential problems
    - Uninitialized variables, type errors, ...
  - Improve ("optimize") the program

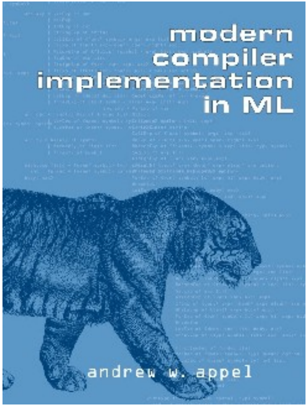
Why take COS320?

You will learn:

- **How high-level languages are translated to machine language**
- How to be a better programmer
  - What can a compiler do?
  - What can a compiler *not* do?
- Lexing & Parsing
- (Some) functional programming in OCaml
- A bit of programming language theory
- A bit of computer architecture

Course resources

- **Website**: `http://www.cs.princeton.edu/courses/archive/spr24/cos320/`
  - Assignments available through **canvas**
  - Discussion forum on **ed**
- **Office hours**: Monday 2:00-3:00pm (Zak), more TBA or by appointment
- Recommended textbook:
  Modern compiler implementation in ML (Appel)
- Real World OCaml (Minsky, Madhavapeddy, Hickey)
  `realworldocaml.org`



Grading

Homework teaches the practice of building a compiler; midterm & final skew towards theory.

- 60% Homework
  - 5 assignments, not evenly weighted
  - Expect homework to be time consuming!
- 20% Midterm
  - Thursday March 7, in class
- 20% Final

Homework policies

- Homework can be done individually or in pairs
- Due on Mondays at 11pm, with 1 hour grace period
- Can be submitted max 4 days late. 10% penalty per day late, with first four late days (across all assignments) waived.
- Feel free to discuss with others at **conceptual** level.
  Submitted work should be your own.

Compilers

(Programming) language = syntax + semantics

- **Syntax**: what sequences of characters are valid programs?
  - Typically specified by context-free grammar

```
<expr> ::= <integer>
         | <variable>
         | <expr> + <expr>
         | <expr> * <expr>
         | (<expr>)
```

- **Semantics**: what is the behavior of a valid program?
  - *Operational semantics*: how can we execute a program?
    - In essence: an interpreter
  - *Axiomatic semantics*: what can we prove about a program?
  - *Denotational semantics*: what mathematical function does the program compute?

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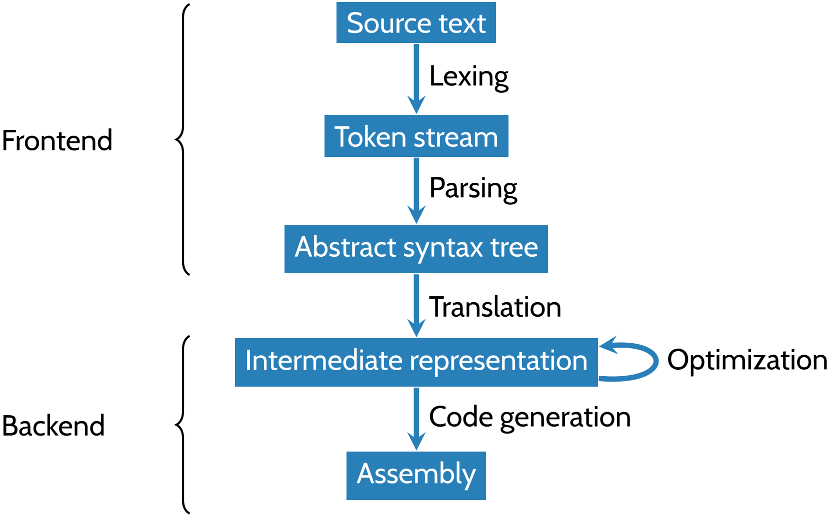
  - *Denotational semantics*: what mathematical function does the program compute?

The job of a compiler is to translate from the syntax of one language to another, but preserve the semantics.

```
#include <stdio.h>

int factorial(int n) {
  int acc = 1;
  while (n > 0) {
    acc = acc * n;
    n = n - 1;
  }
  return acc;
}

int main(int argc, char *argv[]) {
  printf("factorial(6) = %d\n", factorial(6));
}
```

```
factorial:
    movl   $1, %rax
    cmpq   $2, %rdi
    jl     .LBB0_2
.LBB0_1:
    imulq  %rdi, %rax
    decq   %rdi
    cmpq   $1, %rdi
    jg     .LBB0_1
.LBB0_2:
    retq

main:
    movl   $.str, %rdi
    movl   $720, %rsi
    callq  printf
    retq

.globl  .str
.str:
    .asciz  "Factorial·is·%ld\n"
```

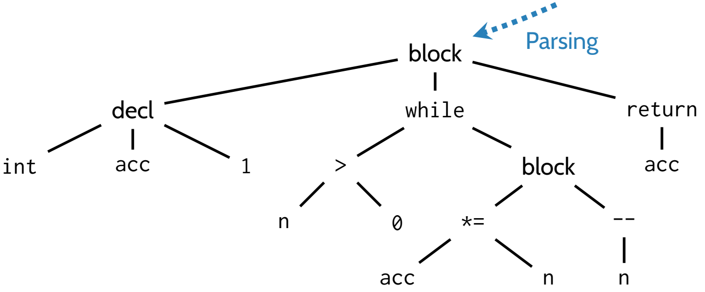
Compiler phases (simplified)

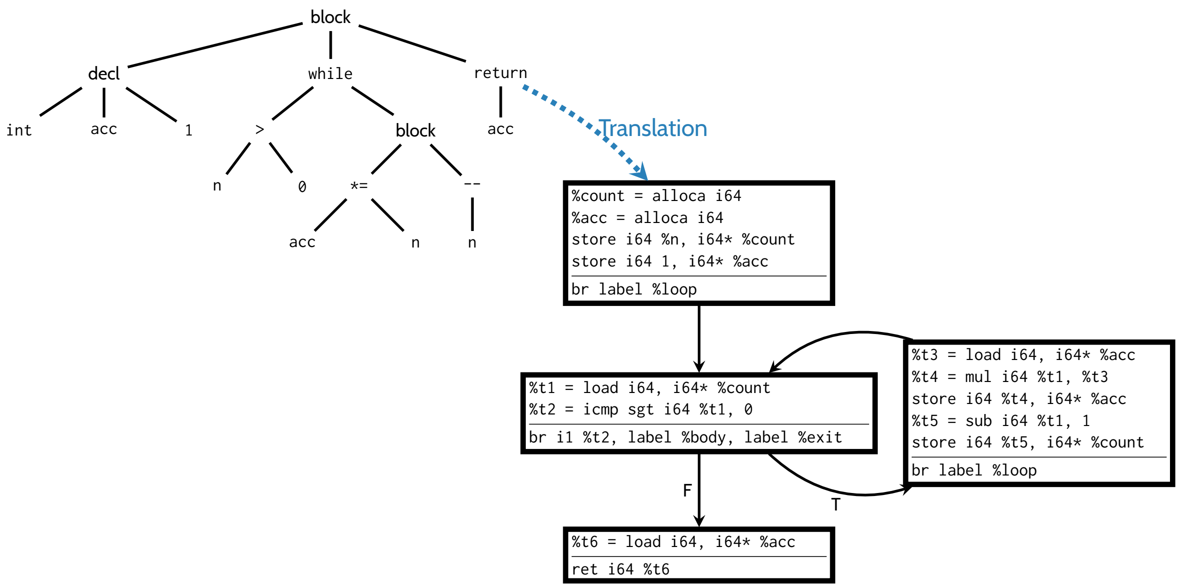


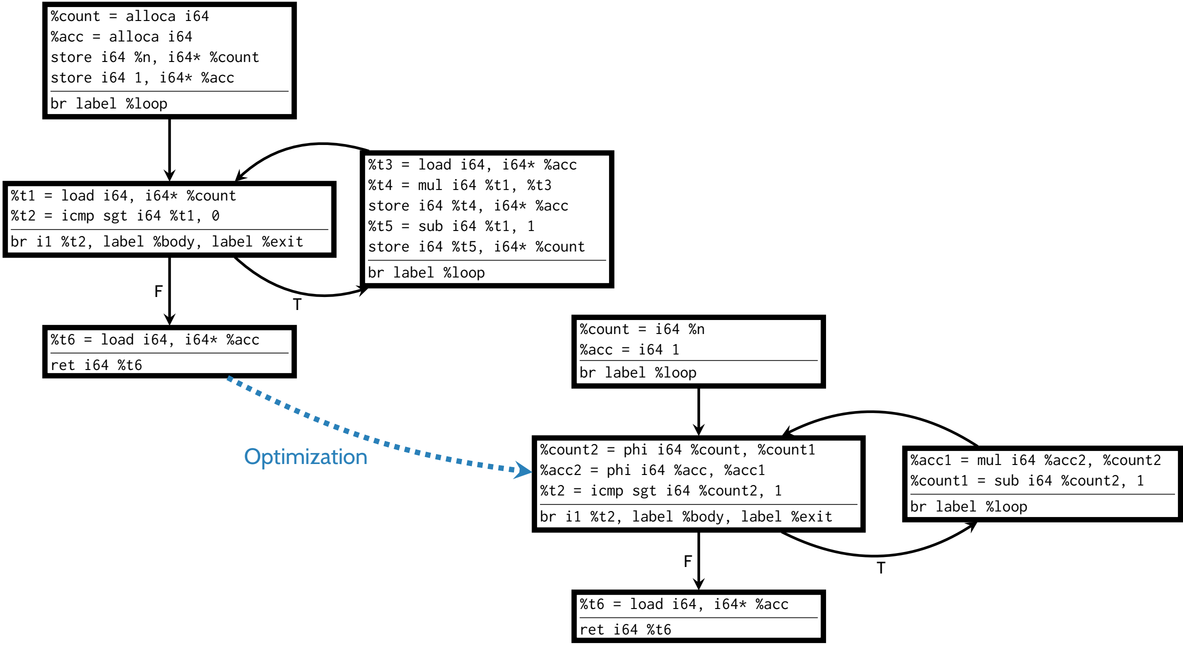
Lexing

```
int acc = 1;
while (n > 0) {
  acc *= n;
  n --;
}
return acc;
```

```
INT, IDENT "acc", EQUAL, INT 1, SEMI,
WHILE, LPAREN, IDENT "n", GT, INT 0, RPAREN, LBRACE,
IDENT "acc", TIMESEQUAL, IDENT "n", SEMI,
IDENT "n", DECREMENT, SEMI,
RBRACE
RETURN, IDENT "acc", SEMI
```




block
decl
while
return
int
acc
1
>
block
acc
n
0
*=
--
acc
n
n
Translation
%count = alloca i64
%acc = alloca i64
store i64 %n, i64* %count
store i64 1, i64* %acc
br label %loop
%t1 = load i64, i64* %count
%t2 = icmp sgt i64 %t1, 0
br i1 %t2, label %body, label %exit
%t3 = load i64, i64* %acc
%t4 = mul i64 %t1, %t3
store i64 %t4, i64* %acc
%t5 = sub i64 %t1, 1
store i64 %t5, i64* %count
br label %loop
F
T
%t6 = load i64, i64* %acc
ret i64 %t6



%count = alloca i64
%acc = alloca i64
store i64 %n, i64* %count
store i64 1, i64* %acc
br label %loop
%t1 = load i64, i64* %count
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br i1 %t2, label %body, label %exit
%t3 = load i64, i64* %acc
%t4 = mul i64 %t1, %t3
store i64 %t4, i64* %acc
%t5 = sub i64 %t1, 1
store i64 %t5, i64* %count
br label %loop
F
T
%t6 = load i64, i64* %acc
ret i64 %t6
Optimization
%count = i64 %n
%acc = i64 1
br label %loop
%count2 = phi i64 %count, %count1
%acc2 = phi i64 %acc, %acc1
%t2 = icmp sgt i64 %count2, 1
br i1 %t2, label %body, label %exit
%acc1 = mul i64 %acc2, %count2
%count1 = sub i64 %count2, 1
br label %loop
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%t6 = load i64, i64* %acc
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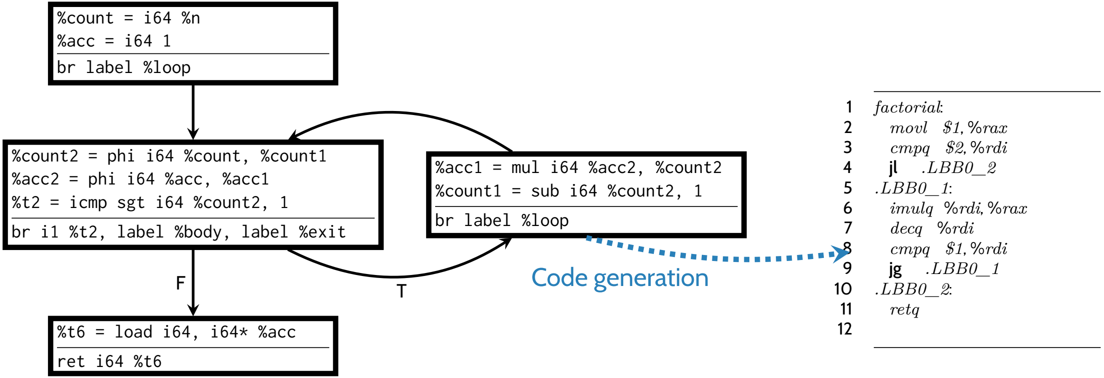
%count = i64 %n
%acc = i64 1
br label %loop
%count2 = phi i64 %count, %count1
%acc2 = phi i64 %acc, %acc1
%t2 = icmp sgt i64 %count2, 1
br i1 %t2, label %body, label %exit
%acc1 = mul i64 %acc2, %count2
%count1 = sub i64 %count2, 1
br label %loop
F
T
%t6 = load i64, i64* %acc
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Code generation
factorial:
movl $1, %rax
cmpq $2, %rdi
jl .LBB0_2
.LBB0_1:
imulq %rdi, %rax
decq %rdi
cmpq $1, %rdi
jg .LBB0_1
.LBB0_2:
retq

COS320 assignments

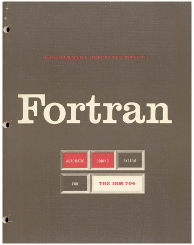
By the end of the course, you will build (in OCaml) a complete compiler from a high-level type-safe language ("Oat") to a subset of x86 assembly.

- HW1: X86lite interpreter
- HW2: LLVMlite-to-X86lite code generation
- HW3: Lexing, Parsing, Oat-to-LLVMlite translation
- HW4: Higher-level features
- HW5: Analysis and Optimizations

We will use the assignments from Penn's CIS 341, provided by Steve Zdancevic.

Historical note

- First "modern" compiler for FORTRAN developed at IBM in 1957
    - Grace Hopper's 1951 A-0 loader/linker
- 18 person-years to complete
- Led by John Backus, who won 1977 Turing award



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- First "modern" compiler for FORTRAN developed at IBM in 1957
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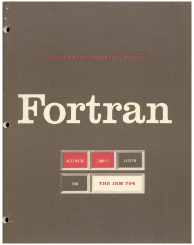
- 18 person-years to complete
- Led by John Backus, who won 1977 Turing award
- You will implement one in a semester



OCaml


modern
compiler
implementation
in Java
andrew w. appel
modern
in C
appel
modern
in ML
appel

- Why OCaml?
  - Algebraic data types + pattern matching are *very* convenient features for writing compilers
- OCaml is a *functional* programming language
  - *Imperative* languages operate by mutating data
  - *Functional* languages operate by producing new data
- OCaml is a *typed* language
  - Contracts on the values produced and consumed by each expression
  - Types are (for the most part) *automatically inferred*.
    - Good style to write types for top-level definitions

- We recommend using VSCode + Docker for OCaml development
  - Each assignment comes with a dev container to make this simple
  - See "Toolchain" instructions on the HW page to get started
- If you have difficulty with installation, ask on ed

- Thursday's lecture: x86lite
    - Simple subset of x86 (~20 instructions)
    - Suitable as a compilation target for Oat
- HW1 on canvas. Due Feb 12.
    - You will implement:
        - A simulator for X86lite machine code
        - An assembler
        - A loader
    - You may work individually or in pairs