COS320: Compiling Techniques

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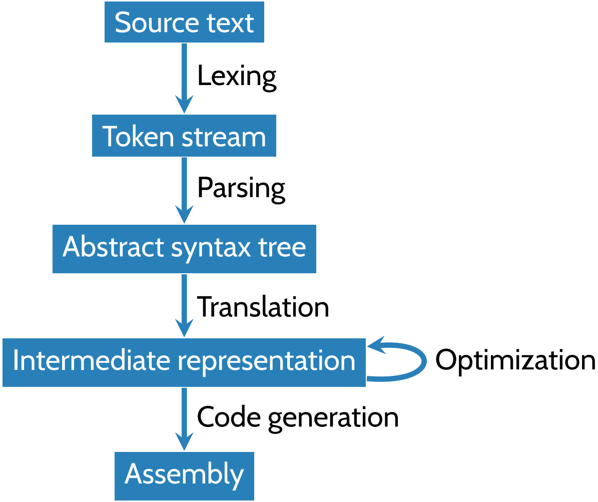
Compiler phases (simplified)



Source text

Lexing

Token stream

Parsing

Abstract syntax tree

Translation

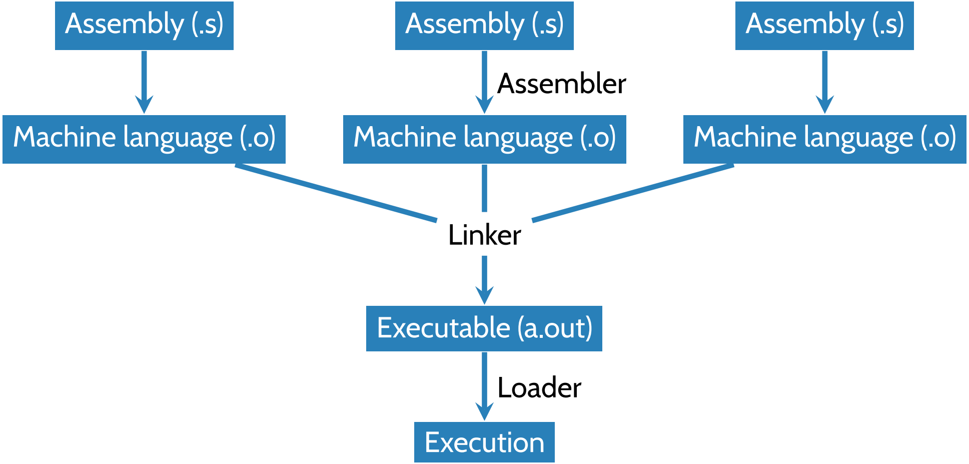
Intermediate representation

Optimization

Code generation

Assembly

After compilation



Assembly (.s)

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Assembler

Machine language (.o)

Machine language (.o)

Machine language (.o)

Linker

Executable (a.out)

Loader

Execution

- Assember (`as`): translate assembly to object file (.o)
  - Object file = machine code + headers for linking & loading
- Linker (`ld`): combine object files into an executable
  - Concatenate data and text sections
  - (Partial) *symbol resolution*: replace symbolic references with addresses
  - *Relocation*: fix references to relocated addresses
- Loader (`exec` family): load executable into memory and transfer control
  - *Dynamic* linking

Today: x86Lite

X86

- X86 is *very* complicated
    - 8-, 16-, 32-, 64-bit values, floats, …
    - Hundreds or thousands of instructions (depending on how they're counted)
    - Variable-length encoding for instructions (1-17 bytes)

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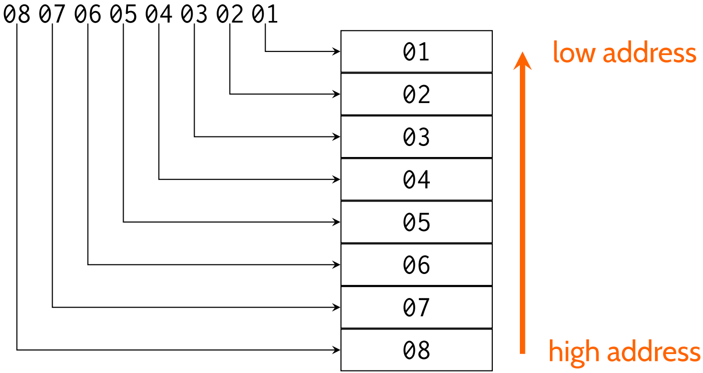
  - 8-, 16-, 32-, 64-bit values, floats, ...
  - Hundreds or thousands of instructions (depending on how they're counted)
  - Variable-length encoding for instructions (1-17 bytes)
- X86lite is a simple subset, still suitable as a compilation target
  - Values are 64-bit integers
  - About 20 instructions
  - Fixed-length encoding for instructions

X86lite machine state

- Memory, consisting of 2^{64} bytes
  - Quadword at `addr` is stored little-endian in **Mem**`[addr]` … **Mem**`[addr+7]` (least significant byte least address)



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- 16 64-bit registers
  - `rax`: general purpose accumulator
  - `rbx`: base pointer, pointer to data
  - `rcx`: counter register for strings & loops
  - `rdx`: data register for I/O
  - `rsi`: pointer register, string source register
  - `rdi`: pointer register, string destination register
  - `rbp`: base pointer, points to the stack frame
  - `rsp`: stack pointer, points to the top of the stack
  - `r08-r15`: general-purpose registers

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- 3 flags (bits)
  - `OF`: (“overflow”) set when result is too big/small to fit in 64 bits
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- `rip`: "virtual" register, points to current instruction
  - `rip` is manipulated only by indirect jumps and return

Anatomy of an x86lite progam

```
factorial:
    cmpq    %rdi, $0
    je      .L4
    movq    $1, %rax
    movq    $0, %rdx
.L3:
    imulq   %rdx, %rax
    addq    $1, %rdx
    cmpq    %rdx, %rdi
    jne     .L3
    retq
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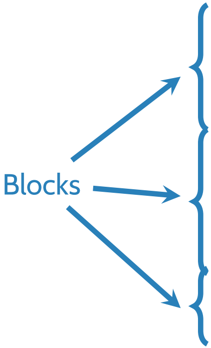

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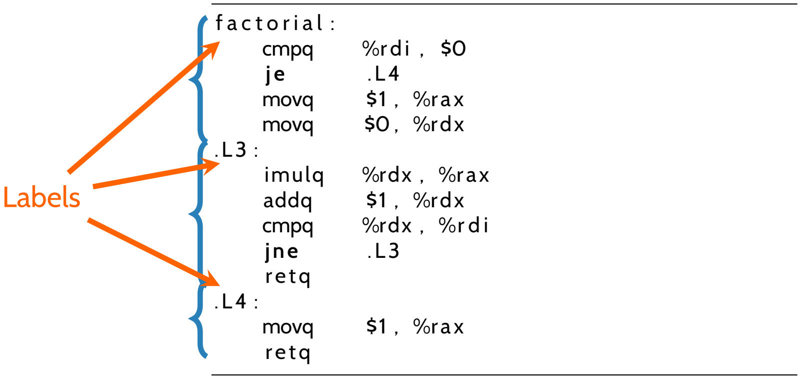

Labels

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X86Lite instructions

- Instruction = opcode + operand list
  - AT&T syntax: `movq $42, %rax` stores the number 42 in `rax`
    - `$` prefix denotes immediate (constant)
    - `%` prefix denotes register
    - `q` suffix denote quadword
  - Intel notation: `mov rax 42`
    - Swap source & destination
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    - Swap source & destination
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- Opcodes (**full specification on course webpage**)
  - Arithmetic: `addq`, `imulq`, `subq`, `negq`, `incq`, `decq`
  - Logic: `andq`, `orq`, `notq`, `xorq`
  - Bit-manipulation: `sarq`, `shlq`, `shrq`, `setb`
  - Data-movement: leaq, `movq`, `pushq`, `popq`
  - Control flow: `cmpq`, `jmp`, `callq`, `retq`, `j CC`

X86Lite Operands

- `Imm` (“immediate”) 64-bit literal signed integer
  - `42`, `0x3de7`
- `Lbl` (“label”) symbolic machine address (to be resolved by assembler/linker/loader)
  - `_factorial`, `.L2`
- `Reg` (“register”)
  - `%rax`, `%r04`
- `Ind` (“indirect”) memory address
  - `(%rax)`, `-8(%rbp)`

X86 Addressing

- Three components of an indirect address: Disp(Base, Index, Scale)
  - Base: a machine address stored in a register
  - Index & Scale: a variable offset from the base (not in x86lite)
  - Disp: displacement/offset (optional)
- Refers to the location **Mem**`[Base + Index * Scale + Disp]`
  - `movq (%rsp), %rax` retrieves **Mem**`[rsp]` and stores it in `rax`
  - `movq -8(%rsp), %rax` retrieves **Mem**`[rsp - 8]` and stores it in `rax`
  - `movq %rax, (%rsp)` stores value of `rax` in **Mem**`[rsp]`.

Control flow

- Three condition flags:
  - `OF`: ("overflow") set when result is to big/small to fit in 64 bits
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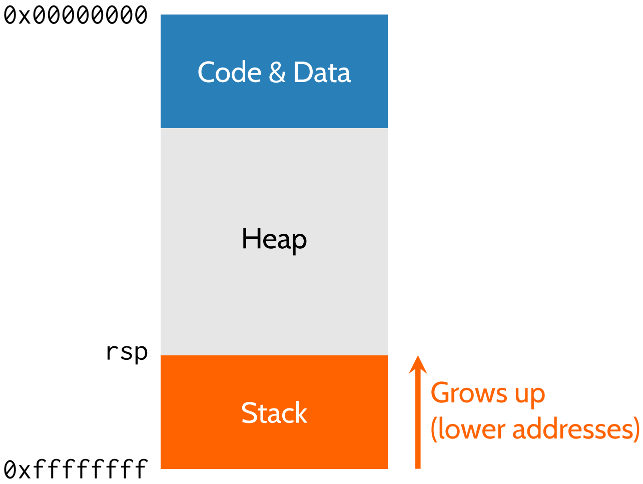
- Instruction `cmpq SRC1, SRC2`: compute `SRC2-SRC1` and set flags
- Instruction `j CC SRC`: jump if to `SRC` if condition code `CC` is set
  - `e` (“equality”): `ZF` set
  - `ne` (“inequality”): `ZF` clear
  - `g` (“greater than”): `SF` clear and `ZF` clear
  - `l` (“less than”): `SF` not equal to `OF`
  - `ge` (“greater than or equal”): `SF` clear
  - `le` (“less than or equal”): `SF` not equal to `OF` or `ZF` set

Conventions

Memory layout



Stack operations

- `%rsp`: pointer to the top of the stack
- `pushq SRC`
  ```
  rsp := rsp - 8
  Mem[rsp] := SRC
  ```
- `popq DEST`
  ```
  DEST := Mem[rsp]
  rsp := rsp + 8
  ```
- `callq SRC`
  ```
  pushq rip
  rip := SRC
  ```
- `retq`
  ```
  popq rip
  ```

Calling conventions

- Implementation of function calls is up to the compiler
  - How are parameters passed?
  - How is return value passed back?
  - How is the return address stored?
  - Which registers is a function allowed to change?
    - caller save: freely usable by called code
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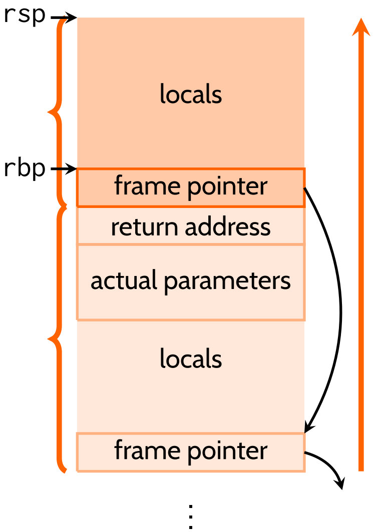
- A *calling convention* is a contract that specifies the structure of the stack and the interface between function *caller* and *callee*
- Useful to standardize on a single convention across the whole system
  - x86-64 AMD System V ABI on 64-bit x86
  - cdecl (“C declaration”) on 32-bit x86

The call stack

- Function calls are implemented using a *stack* of **activation records** (aka **stack frames**)
- Each activation record contains:
  - Frame pointer (start address of previous frame)
  - Local variables
- Except for current frame, also contains:
  - Actual parameters (arguments)
  - Return address



Caller protocol

Suppose we call function with parameters v_1, ..., v_n

1. Save caller-save registers, if needed
2. Store first six actual parameters $v_1, \ldots, v_6$ in `rdi`, `rsi`, `rdx`, `rcx`, `r08`, `r09`
3. Push v_n,...,v_7
    - nth actual parameter is located at **Mem**`[rbp + 8*(`*n*`-5)]`
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After call:

1. De-allocate pushed actual parameters
2. Restore caller-save registers, if needed

Callee protocol

On entry:

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3. Allocate local storage

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On exit:

1. Store return value in `rax`
2. Deallocate local storage
3. Restore previous `rbp`

```c
long factorial(long n) {
  long i;
  long result = 1;
  for (i = 1; i < n; i++) {
    result *= i;
  }
  return result;
}
```

```
factorial:
    cmpq    %rdi, $0
    jle     .L4
    movq    $1, %rax
    movq    $1, %rdx
.L3:
    imulq   %rdx, %rax
    addq    $1, %rdx
    cmpq    %rdx, %rdi
    jne     .L3
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.L4:
    movq    $1, %rax
    retq
```

x86-64 System V AMD 64 ABI

- Callee-save: `rbp`, `rbx`, `r12-r15`
- Caller-save: all others
- Store return value in `rax` (second return value in `rdx`)
- Parameters:
  - Parameters 1-6 in `rdi`, `rsi`, `rdx`, `rcx`, `r08`, `r09`
  - Parameters 7-n in `16(rbp)`, `24(rbp)`, … `(8*(`*n*`-5))(rbp)`
- 128 byte “red zone” below `rsp`
  - Not modified by signal / interrupt handlers
  - Useful for storing local data of leaf functions