CS 4120
Introduction to Compilers

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Lecture 19: Introduction to Optimization

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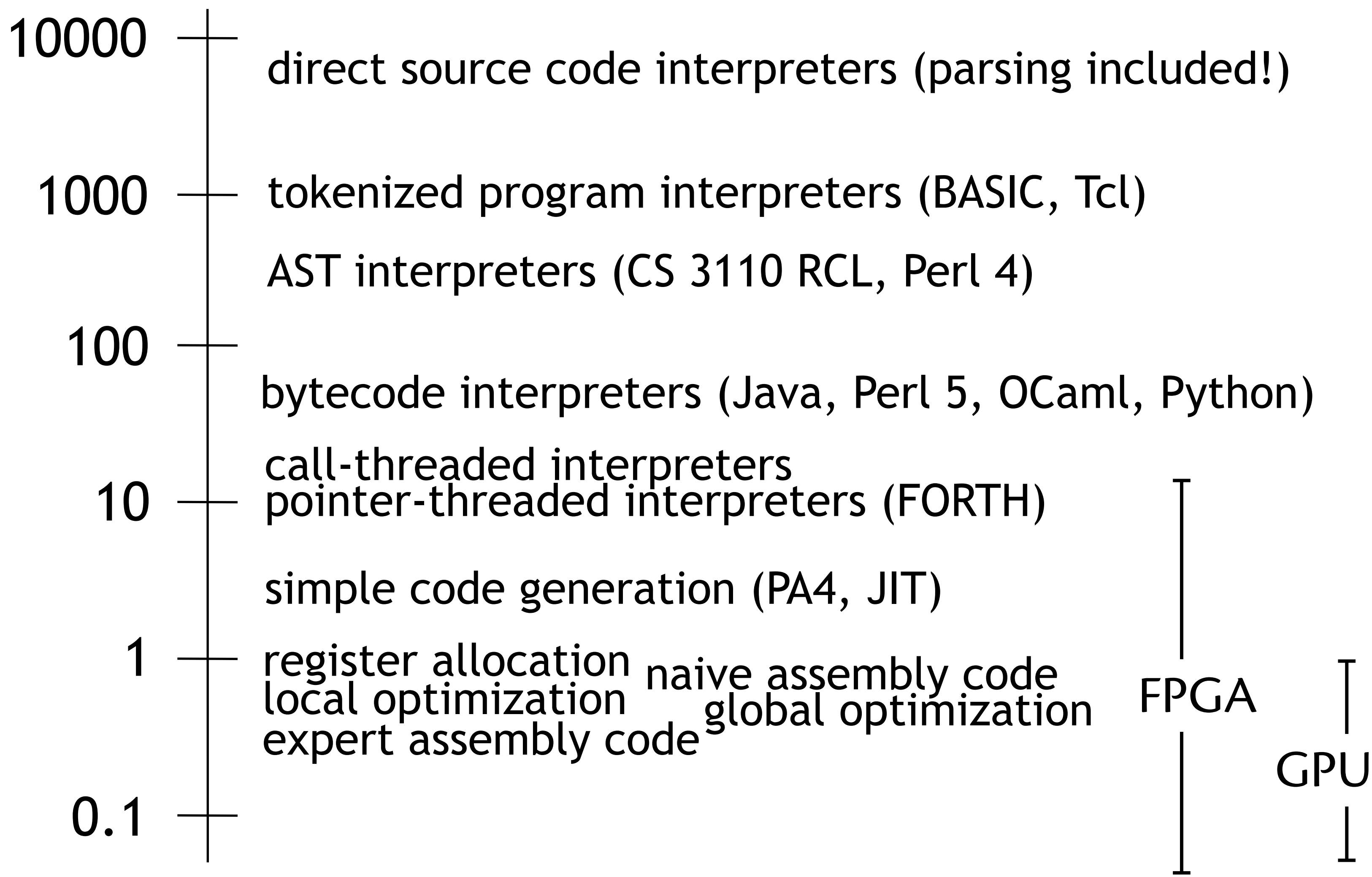
Optimization

- Next topic: how to generate better code through **optimization.**
- This course covers the most valuable and straightforward optimizations – much more to learn!
  - Other sources:
    - Muchnick has 10 chapters of optimization techniques
    - Cooper and Torczon also cover optimization

How fast can you go?



Goal of optimization

- Help programmers
  - clean, modular, high-level source code
  - but compile to assembly-code performance
- Optimizations are code transformations
  - can't change meaning of program to behavior not allowed by source.
- Different kinds of optimization:
  - space optimization: reduce memory use
  - time optimization: reduce execution time
  - power optimization: reduce power usage

Why do we need optimization?

- Programmers may write suboptimal code for clarity.
- High-level language may make it inconvenient or impossible to avoid redundant computation

```
a[i][j] = a[i][j] + 1
```

- Architectural independence.
- Modern architectures assume optimization—hard to optimize by hand.

Where to optimize?

- Usual goal: improve time performance
- But: many optimizations trade off space vs. time.
- Example: loop unrolling replaces a loop body with N copies.
  - Increasing code space speeds up one loop, slows rest of program down a little.
  - Frequently executed loops with many iterations: space/time tradeoff is generally a win.
  - Infrequently executed code: optimize code space at expense of time, saving space in instruction cache, TLB
  - Complex optimizations may never pay off!
- Focus of optimization: program **hot spots**

Safety

- Possible opportunity for **loop-invariant code motion:**

```
while (b) {
        z = y/x; // x, y not assigned in loop
        …
}
```

- Transformation: invariant code out of loop:

```
z = y/x;
while (b) {
        …
}
```

Preserves meaning?

Faster?

Three aspects of an optimization:

1. the code transformation
2. safety of transformation
3. performance improvement

How to write fast programs

1. Pick the right algorithms and data structures: design for locality and few operations.
2. Turn on optimization and **profile** to figure out program hot spots.
3. Evaluate whether design works; if so…
4. Tweak source code until optimizer does “the right thing” to machine code.
   – understanding optimizers helps!

Structure of an optimization

- Optimization is a code transformation
- Applied at some stage of compiler (HIR, MIR, LIR)
- In general, requires some analysis:
  - safety analysis to determine where transformation does not change meaning (e.g. live variable analysis)
  - cost analysis to determine where it ought to speed up code (e.g., which variable to spill)

When to apply optimization

HIR	AST	Inlining Specialization
	IR	Constant folding Constant propagation Value numbering Dead code elimination
MIR	Canonical IR	Loop-invariant code motion Common sub-expression elimination Strength reduction Constant folding& propagation (again)
	Abstract Assembly	Branch prediction/optimization Register allocation
LIR		Loop unrolling Cache optimization
	Assembly	Peephole optimizations

Register allocation

- Goal: convert abstract assembly (infinite no. of registers) into real assembly (6 registers)

```
mov t1,t2
add t1,[rbp—8]
mov t3,[rbp-16]
mov t4,t3
cmp t1,t4
```

```
mov rax, rbx
add rax, [rbp-8]
mov rbx, [rbp-16]

cmp rax, rbx
```

Try to reuse registers aggressively (e.g., **`rbx = t2, t3, t4`**)

- Coalesce registers (t3, t4) to eliminate **`mov`**'s
- In general, must **spill** some temporaries to stack

Constant folding

- Idea: if operands are known at compile time, evaluate at compile time when possible.

int x = (2 + 3)*4*y; ⇒ int x = 5*4*y;

⇒ int x = 20*y;

- Easy and useful at every stage of compilation
  - Constant expressions are created by translation and by other optimizations

a[2] ⇒ MEM(TEMP(a) + 2*4)

⇒ MEM(TEMP(a) + 8)

Constant folding conditionals

if (true) S ⇒ S

if (false) S ⇒ {}

if (true) S else S’ ⇒ S

if (false) S else S’ ⇒ S’

while (false) S ⇒ {}

if (2 > 3) S ⇒ if (false) S ⇒ {}

Algebraic simplification

- More general form of constant folding: take advantage of simplification rules

$a * 1 \Rightarrow a$ $a * 0 \Rightarrow 0$

$a + 0 \Rightarrow a$

$b \mid false \Rightarrow b$ $b \;\&\; true \Rightarrow b$

identities

$(a + 1) + 2 \Rightarrow a + (1 + 2) \Rightarrow a+3$

reassociation

$a * 4 \Rightarrow a \text{ shl } 2$

$a * 7 \Rightarrow (a \text{ shl } 3) - a$

strength reduction

$a / 32767 \Rightarrow a \text{ shr } 15 + a \text{ shr } 30 + a \text{ shr } 45 + a \text{ shr } 60$

- Be careful with floating point and overflow — algebraic identities may give wrong or less precise answers.
  - E.g., $(a+b)+c \neq a+(b+c)$ in floating point if a, b small.

Unreachable code elimination

- Basic blocks not contained by any trace leading from starting basic block are **unreachable** and can be eliminated
- Performed at canonical IR or assembly code levels
- Reductions in code size improve cache, TLB performance.
- ≠ dead code elimination

Inlining

- Replace a function call with the body of the function:

```
f(a: int):int = { b:int=1;   n:int = 0
                 while (n<a) {b = 2*b; return b }}
g(x: int):int  = { return 1 + f(x) }
⇒ g(x:int):int = { fx:int { a:int = x

                     { b:int=1; n:int=0;
                       while (n<a) { b = 2*b; fx=b }}
                  return 1 + fx; }
```

- Best done on HIR
- Can inline methods, but more difficult – there can be only one f.
- May need to rename variables to avoid **name capture**—what if f refers to a global variable x?

Specialization

- Idea: create specialized versions of functions (or methods) that are called from different places w/ different args

```
class A implements I { m( ) {…} }
class B implements I { m( ) {…} }
f(x: I) { x.m( ); } // don’t know which m
a = new A(); f(a)// know A.m
b = new B(); f(b)// know B.m
```

- Can inline methods when implementation is known
- Impl. known e.g. if only one implementing class
- Can specialize inherited methods (e.g., HotSpot JIT)

Constant propagation

- If value of variable is known to be a constant, replace use of variable with constant
- Value of variable must be propagated forward from point of assignment

```
int x = 5;
int y = x*2;
int z = a[y]; // = MEM(TEMP(a) + y*8)
```

- Interleave with constant folding!

Dead code elimination

- If side effect of a statement can never be observed, can eliminate the statement

```
x = y*y;        // dead!
…               // x unused        ⇒   …
x = z*z;                               x = z*z;
```

- **Dead variable:** if never read after defn. (exc. to update other dead vars)

```
int i;
while (m<n) { m++; i = i+1}   ⇒   while (m<n) {m++}
```

  - Other optimizations create dead statements, variables

Copy propagation

- Given assignment x = y, replace subsequent uses of x with y
- May make x a dead variable, result in dead code
- Need to determine where copies of y (definitely) propagate to

x = y
if (x > 1)
  x = x * f(x – 1)

~~x = y~~ *dead code*
if (y > 1) {
  x = y * f(y – 1)

Redundancy Elimination

- Common Subexpression Elimination (CSE) combines redundant computations

```
  a[i] = a[i] + 1
⇒ [a+i*8] = [a+i*8] + 1
⇒ t1 = a + i*8; [t1] = [t1]+1
```

- Need to determine that expression always has same value in both places

```
b[j]=a[i]+1; c[k]=a[i] ⇒ t1=a[i]; b[j]=t1+1; c[k]=t1  ?
```

Loops

- Program *hot spots* are usually loops (exceptions: OS kernels, compilers)
- Most execution time in most programs is spent in loops: 90/10 is typical.
- Loop optimizations: important, effective, and numerous

Loop-invariant code motion

- A form of redundancy elimination
- If result of a statement or expression does not change during loop, *and* it has no externally-visible side effect (!), can **hoist** before loop

```
for (i = 0; i < a.length; i++) {
    // a not assigned in loop
}
```

hoisted loop-invariant expression

```
t1 = a.length ;
for (i = 0; i < t1; i++) {
    ...
}
```

Strength reduction

- Replace expensive operations (*,/) by cheap ones (+, –) via **dependent induction variable**

```
for (int i = 0; i < n; i++) {
  a[i*3] = 1;
}
```

$j == 3*i$

```
int j = 0;
for (int i = 0; i < n; i++) {
     a[j] = 1; j = j+3;
}
```

Loop unrolling

- Branches are expensive; **unroll** loop to avoid them:

```
for (i = 0; i<n; i++) { S }
```

$\Downarrow$

```
for (i = 0; i < n−3; i+=4) {S; S; S; S;}
for (      ; i < n; i++) { S }
```

- Eliminate ¾ of conditional branches!
- Space-time tradeoff: not a good idea for large S or small n.

Summary

- Many useful optimizations that can transform code to make it faster/smaller/...
- Whole is greater than sum of parts: optimizations should be applied together, sometimes more than once, at different levels.
- The hard problem: when are optimizations are safe and when are they effective?

$\Rightarrow$ **Dataflow analysis**

$\Rightarrow$ **Control flow analysis**

$\Rightarrow$ **Pointer analysis**