7. Optimization

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Lecture notes courtesy Marcus Denker
Roadmap

> Introduction
> Optimizations in the Back-end
> The Optimizer
> SSA Optimizations
> Advanced Optimizations
Literature

> Muchnick: *Advanced Compiler Design and Implementation*  
  — >600 pages on optimizations

> Appel: *Modern Compiler Implementation in Java*  
  — *The basics*
Roadmap

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Optimization: The Idea

- Transform the program to improve efficiency
- **Performance**: faster execution
- **Size**: smaller executable, smaller memory footprint

**Tradeoffs:**

1) **Performance** vs. **Size**
2) **Compilation speed** and **memory**
No Magic Bullet!

> Rice (1953): *For every compiler there is a modified compiler that generates shorter code.*

> **Proof:** Assume there is a compiler U that generates the shortest optimized program Opt(P) for all P.
  — Assume P to be a program that does not stop and has no output
  — Opt(P) will be L1 goto L1
  — Halting problem. Thus: U does not exist.

> There will be always a better optimizer!
  — Job guarantee for compiler architects :-)
Optimization at many levels

> Optimizations both in the optimizer and back-end
Roadmap

- Introduction
- **Optimizations in the Back-end**
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Optimizations in the Backend

- Register Allocation
- Instruction Selection
- Peep-hole Optimization
Register Allocation

> Processor has only finite amount of registers
  — Can be very small (x86)

> Temporary variables
  — non-overlapping temporaries can share one register

> Passing arguments via registers

> Optimizing register allocation very important for good performance
  — Especially on x86
Instruction Selection

> For every expression, there are many ways to realize them for a processor

> Example: Multiplication*2 can be done by bit-shift

*Instruction selection is a form of optimization*
Peephole Optimization

> Simple local optimization
> Look at code “through a hole”
  —replace sequences by known shorter ones
  —table pre-computed

```plaintext
code:
store R, a;
load a, R
imul 2, R;

optimized:
store R, a;
ashl 1, R;
```

*Important when using simple instruction selection!*
Optimization at many levels

Most optimization is done in a special phase
Roadmap

> Introduction
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> **The Optimizer**
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> Advanced Optimizations
Examples for Optimizations

- Constant Folding / Propagation
- Copy Propagation
- Algebraic Simplifications
- Strength Reduction
- Dead Code Elimination
  — Structure Simplifications
- Loop Optimizations
- Partial Redundancy Elimination
- Code Inlining
Constant Folding

> Evaluate constant expressions at compile time
> Only possible when side-effect freeness guaranteed

\[
c := 1 + 3 \quad \Rightarrow \quad c := 4
\]

\[
\text{true not} \quad \Rightarrow \quad \text{false}
\]

Caveat: Floats — implementation could be different between machines!
> Variables that have constant value, e.g. $c := 3$
  — Later uses of $c$ can be replaced by the constant
  — If no change of $c$ between!

```
b := 3
c := 1 + b
d := b + c
```

```
b := 3
c := 1 + 3
d := 3 + c
```

Analysis needed, as $b$ can be assigned more than once!
Copy Propagation

> for a statement \( x := y \)
> replace later uses of \( x \) with \( y \), if \( x \) and \( y \) have not been changed.

\[
\begin{align*}
  x & := y \\
  c & := 1 + x \\
  d & := x + c
\end{align*}
\]

\[
\begin{align*}
  x & := y \\
  c & := 1 + y \\
  d & := y + c
\end{align*}
\]

Analysis needed, as \( y \) and \( x \) can be assigned more than once!
> Use algebraic properties to simplify expressions

\[ -(-i) \rightarrow i \]

\[ b \ or: \ true \rightarrow true \]

*Important to simplify code for later optimizations*
Strength Reduction

> Replace expensive operations with simpler ones
> Example: Multiplications replaced by additions

\[
\begin{align*}
y &:= x \times 2 \\
y &:= x + x
\end{align*}
\]

*Peephole optimizations are often strength reductions*
Dead Code

> Remove *unnecessary* code
  —e.g. variables assigned but never read

```
b := 3
```
```
c := 1 + 3
d := 3 + c
```
```
c := 1 + 3
d := 3 + c
```

> Remove code never reached

```
if (false)
    {a := 5}
```
```
if (false)
    {}
```
Similar to dead code: Simplify CFG Structure
- Eg delete empty basic blocks, fuse basic blocks (next slides)

Optimizations will degenerate CFG
- Needs to be cleaned to simplify further optimization!
Delete Empty Basic Blocks

\[ a = 1 \]

\[ b = a \]

\[ \ldots b \ldots \]

\[ a = 1 \]

\[ b = a \]

\[ \ldots b \ldots \]
Fuse Basic Blocks
Common Subexpression Elimination (CSE)

> **Common Subexpression:**
  > There is another occurrence of the expression whose evaluation always precedes this one
  > — operands remain unchanged

> **Local** (inside one basic block): When building IR

> **Global** (complete flow-graph)
Example CSE

\[
\begin{align*}
b &:= a + 2 \\
c &:= 4 \times b \\
&\quad \text{\(b < c\)?} \\
d &:= a + 2
\end{align*}
\]

\[
\begin{align*}
t1 &:= a + 2 \\
b &:= t1 \\
c &:= 4 \times b \\
&\quad \text{\(b < c\)?} \\
d &:= t1
\end{align*}
\]
Loop Optimizations

> Optimizing code in loops is important
  — often executed, large payoff

> Various techniques
  – fission/fusion: split/combine loops to improve locality or reduce overhead
  – scheduling: run parts in multiple processors
  – unrolling: duplicate body several times to decrease test cost
  – loop-invariant code motion: move invariant code out of loop
  – ...

http://en.wikipedia.org/wiki/Loop_optimization
Loop Invariant Code Motion

Move expressions that are constant over all iterations out of the loop
Induction Variable Optimizations

Values of variables form an arithmetic progression

integer a(100)
do i = 1, 100
  a(i) = 202 - 2 * i
endo

value assigned to a decreases by 2

integer a(100)
t1 := 202
do i = 1, 100
  t1 := t1 - 2
  a(i) = t1
endo

uses Strength Reduction
Partial Redundancy Elimination (PRE)

- Combines multiple optimizations:
  - global common-subexpression elimination
  - loop-invariant code motion

- **Partial Redundancy**: computation done more than once on some path in the flow-graph

- PRE: insert and delete code to minimize redundancy.
Partial Redundancy Elimination

if (some_condition) {
    // some code
    y = x + 4;
}
else {
    // other code
}
z = x + 4;

if (some_condition) {
    // some code
    t = x + 4;
    y = t;
}
else {
    // other code
    t = x + 4;
}
z = t;

http://en.wikipedia.org/wiki/Partial_redundancy_elimination
> All optimizations up to now were local to one procedure

> **Problem:** procedures or functions are very short
  — Especially in good OO code!

> **Solution:** Copy code of small procedures into the caller
  — OO: Polymorphic calls. Which method is called?

[en.wikipedia.org/wiki/Inline_caching](en.wikipedia.org/wiki/Inline_caching)
Example: Inlining

\[ a := \text{power2}(b) \]

\[
\text{power2}(x) \{
    \text{return } x \times x
\}
\]

\[ a := b \times b \]
Roadmap

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Recall: SSA

> SSA: Static Single Assignment Form

> **Definition:** Every variable is only assigned once
Properties

> Definitions of variables (assignments) have a list of all uses

> Variable uses (reads) point to the one definition

> CFG of Basic Blocks
Examples: Optimization on SSA

> We take three simple ones:
  — Constant Propagation
  — Copy Propagation
  — Simple Dead Code Elimination
Recall: Constant Propagation

> Variables that have constant value, e.g. c := 3
  — Later uses of c can be replaced by the constant
  — If no change of c between!

```
b := 3
b := 3
```

```
c := 1 + b
c := 1 + 3
```

```
d := b + c
d := 3 + c
```

Analysis needed, as b can be assigned more than once!
Variables are assigned once
We know that we can replace all uses by the constant!

\[
\begin{align*}
b_1 & := 3 \\
c_1 & := 1 + b_1 \\
d_1 & := b_1 + c_1 \\
\end{align*}
\]

\[
\begin{align*}
b_1 & := 3 \\
c_1 & := 1 + 3 \\
d_1 & := 3 + c_1 \\
\end{align*}
\]
Recall: Copy Propagation

> for a statement \( x := y \)
> replace later uses of \( x \) with \( y \), if \( x \) and \( y \) have not been changed.

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x & := y \\
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\begin{align*}
x & := y \\
c & := 1 + y \\
d & := y + c
\end{align*}
\]

Analysis needed, as \( y \) and \( x \) can be assigned more than once!
Copy Propagation and SSA

> for a statement \( x_1 := y_1 \)
> replace later uses of \( x_1 \) with \( y_1 \)

\[
\begin{align*}
x_1 &:= y_1 \\
c_1 &:= 1 + x_1 \\
d_1 &:= x_1 + c_1
\end{align*}
\]

\[
\begin{align*}
x_1 &:= y_1 \\
c_1 &:= 1 + y_1 \\
d_1 &:= y_1 + c_1
\end{align*}
\]
Dead Code Elimination and SSA

> Variable is *live* if the list of uses is not empty.

> Dead definitions can be deleted

— (If there is no side-effect)

```plaintext
b1 := 3
cl := 1 + 3
d1 := 3 + c
```
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Profile-guided optimization

> Approach:
  — Generate code,
  — profile it in a typical scenario,
  — then use that information to optimize it

> Problem:
  — usage scenarios can change in deployment, there is no way to react to that as profile is generated at compile time.
Dynamic optimization

> Re-optimize at run time in the VM
  — uses profile information gathered at run time
  — for both hardware and language VM
  — good way to exploit unused CPU cycles or unused CPUs (multi-core)
> Optimizing for using multiple processors
  — Auto parallelization
  — Very active area of research (again)
Iterative Process

> There is no general “right” order of optimizations
> One optimization generates new opportunities for a preceding one.
> Optimization is an iterative process

Compile Time vs. Code Quality
What you should know!

- Why do we optimize programs?
- Is there an optimal optimizer?
- Where in a compiler does optimization happen?
- Can you explain constant propagation?
Can you answer these questions?

- What makes SSA suitable for optimization?
- When is a definition of a variable live in SSA Form?
- Why don’t we just optimize on the AST?
- Why do we need to optimize IR on different levels?
- In which order do we run the different optimizations?
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