9. Optimization

Marcus Denker
Roadmap

- Introduction
- Optimizations in the Back-end
- The Optimizer
- SSA Optimizations
- Advanced Optimizations
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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!

> There is no perfect optimizer
> Example: optimize for simplicity

Opt(P): Smallest Program

Q: Program with no output, does not stop

Opt(Q)?
No Magic Bullet!

> There is no perfect optimizer
> Example: optimize for simplicity

Opt(P): Smallest Program

Q: Program with no output, does not stop

Opt(Q)?

L1 goto L1
No Magic Bullet!

> There is no perfect optimizer
> Example: optimize for simplicity

\[
\begin{align*}
\text{Opt}(P): & \text{ Smallest Program} \\
\text{Q: Program with no output, does not stop}
\end{align*}
\]

\[
\text{Opt}(Q)?
\]

L1 goto L1

Halting problem!
Another way to look at it...

> 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 :-)

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Optimization on many levels

> Optimizations both in the optimizer and back-end
Roadmap

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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

```
store R,a;
load a,R

imul 2,R;
```

```
store R,a;
ashl 2,R;
```

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

Major work of optimization done in a special phase

Focus of this lecture
Different levels of IR

> Different levels of IR for different optimizations

> Example:
  – Array access as direct memory manipulation
  – We generate many simple to optimize integer expressions

> We focus on high-level optimizations
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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

Caveat: Floats — implementation could be different between machines!
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!

\[
\begin{align*}
  b & := 3 \\
  c & := 1 + b \\
  d & := b + c
\end{align*}
\]

\[
\begin{align*}
  b & := 3 \\
  c & := 1 + 3 \\
  d & := 3 + c
\end{align*}
\]

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.

$x := y$
$c := 1 + x$
$d := x + c$

$x := y$
$c := 1 + y$
$d := y + c$

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

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

\[b \text{ or: true} \rightarrow \text{true}\]

*Important to simplify code for later optimizations*
**Strength Reduction**

> Replace expensive operations with simpler ones

> Example: Multiplications replaced by additions

\[ y := x \times 2 \quad \rightarrow \quad y := x + x \]

*Peephole optimizations are often strength reductions*
Dead Code

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

\[
\begin{align*}
b & := 3 \\
c & := 1 + 3 \\
d & := 3 + c \\
\end{align*}
\]

> Remove code never reached

\[
\begin{align*}
\text{if (false)} \\
\{a := 5\} \\
\end{align*}
\]
Similar to dead code: Simplify CFG Structure

Optimizations will degenerate CFG

Needs to be cleaned to simplify further optimization!
Delete Empty Basic Blocks
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

\[ b := a + 2 \]
\[ c := 4 \times b \]
\[ b < c? \]

\[ b := 1 \]
\[ d := a + 2 \]

\[ t1 := a + 2 \]
\[ b := t1 \]
\[ c := 4 \times b \]
\[ b < c? \]

\[ b := 1 \]
\[ d := t1 \]
Loop Optimizations

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

> All optimizations help when applied to loop-bodies

> Some optimizations are loop specific
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.
Code Inlining

> All optimization up to know where 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?
Example: Inlining

```
a := power2(b)
```

```
power2(x) {
  return x*x
}
```

```
a := b * b
```
Roadmap

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- **SSA Optimizations**
- Advanced Optimizations
Repeat: 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
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!

\[
\begin{align*}
  b & := 3 \\
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\]

\[
\begin{align*}
  b & := 3 \\
  c & := 1 + 3 \\
  d & := 3 + c
\end{align*}
\]

Analysis needed, as \( b \) can be assigned more than once!
Constant Propagation and SSA

- Variables are assigned once
- We know that we can replace all uses by the constant!

```
b1 := 3
cl := 1 + b1
d1 := b1 + cl
```

```
b1 := 3
c1 := 1 + 3
d1 := 3 + c
```
Repeat: Copy Propagation

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

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

Analysis needed, as \( y \) and \( x \) can be assigned more than once!
For a statement $x_1 := y_1$,
replace later uses of $x_1$ with $y_1$

$x_1 := y_1$
$c_1 := 1 + x_1$
$d_1 := x_1 + c_1$

$x_1 := y_1$
$c_1 := 1 + y_1$
$d_1 := y_1 + c_1$
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)
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Advanced Optimizations

> Optimizing for using multiple processors
  > Auto parallelization
  > Very active area of research (again)

> Inter-procedural optimizations
  > Global view, not just one procedure

> Profile-guided optimization

> Vectorization

> Dynamic optimization
  > Used in virtual machines (both hardware and language VM)
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 we have seen...

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Optimization

## Literature

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

- Appel: *Modern Compiler Implementation in Java*
  - The basics
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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