UNIVERSITÄT BERN

9. Optimization

Marcus Denker

Roadmap

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

Roadmap

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

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

Opt(P): Smallest ProgramQ: Program with no output, does not stop

Opt(Q)?

```
L1 goto L1
```

Halting problem!

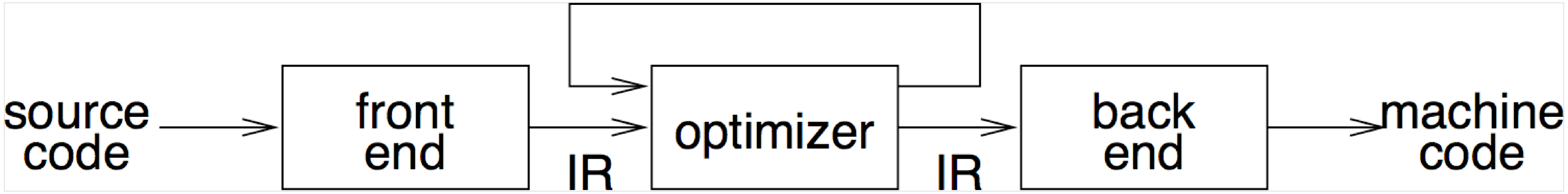
Another way to look at it...

- 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 :-)

Optimization on many levels



> Optimizations both in the optimizer and back-end

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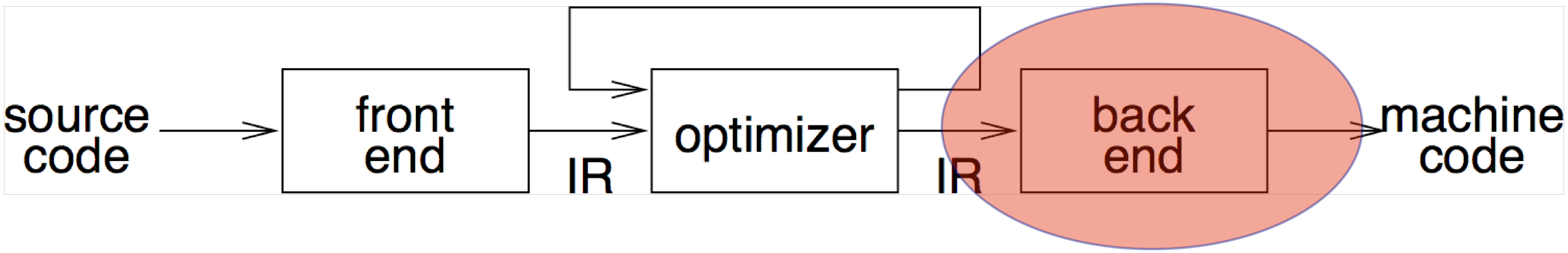
Optimizations in the Backend



- 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

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

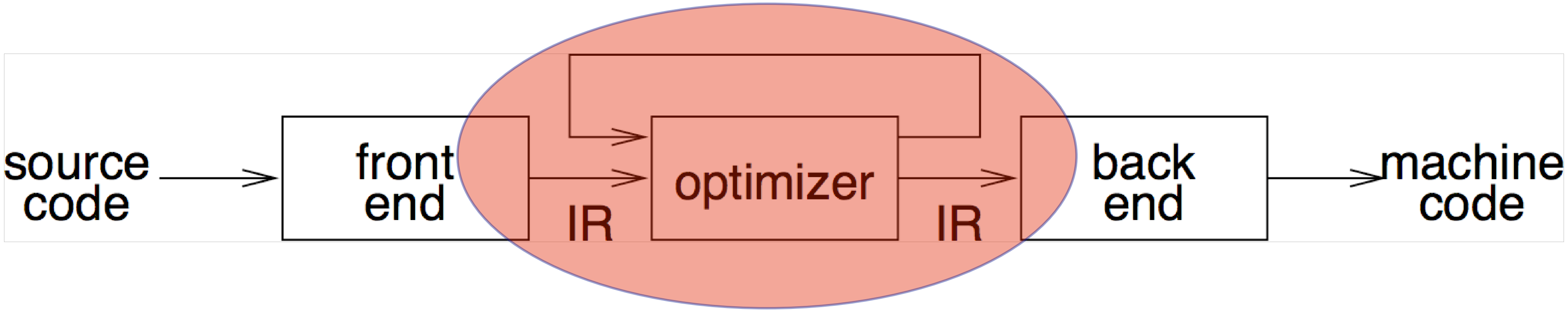
```
store R,a;
```

```
imul 2,R;
```

```
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

```
c:= 1 + 3    →    c:= 4

true not     →    false
```

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!

```
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.

```
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!

Algebraic Simplifications

> Use algebraic properties to simplify expressions

`-(-i)` → `i`

`b or: true` → `true`

Important to simplify code for later optimizations

Strength Reduction

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

```
y := x * 2
```

```
y := x + x
```

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)
{}
```

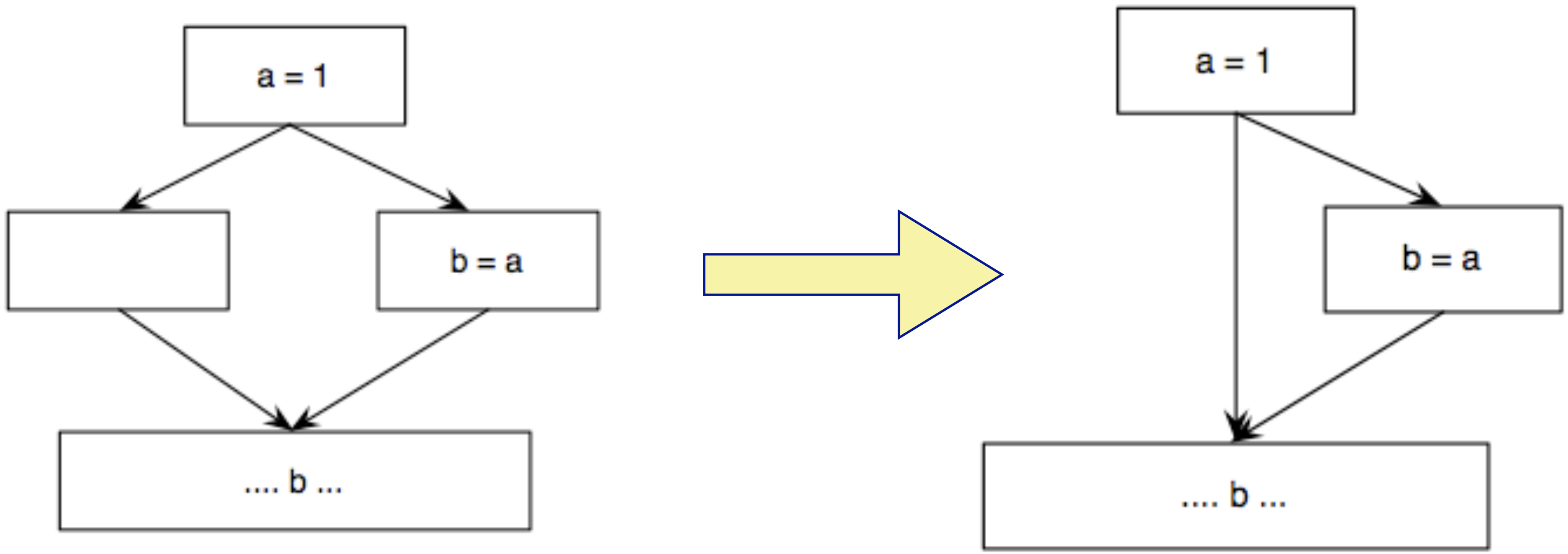
Simplify Structure

> Similar to dead code: Simplify CFG Structure

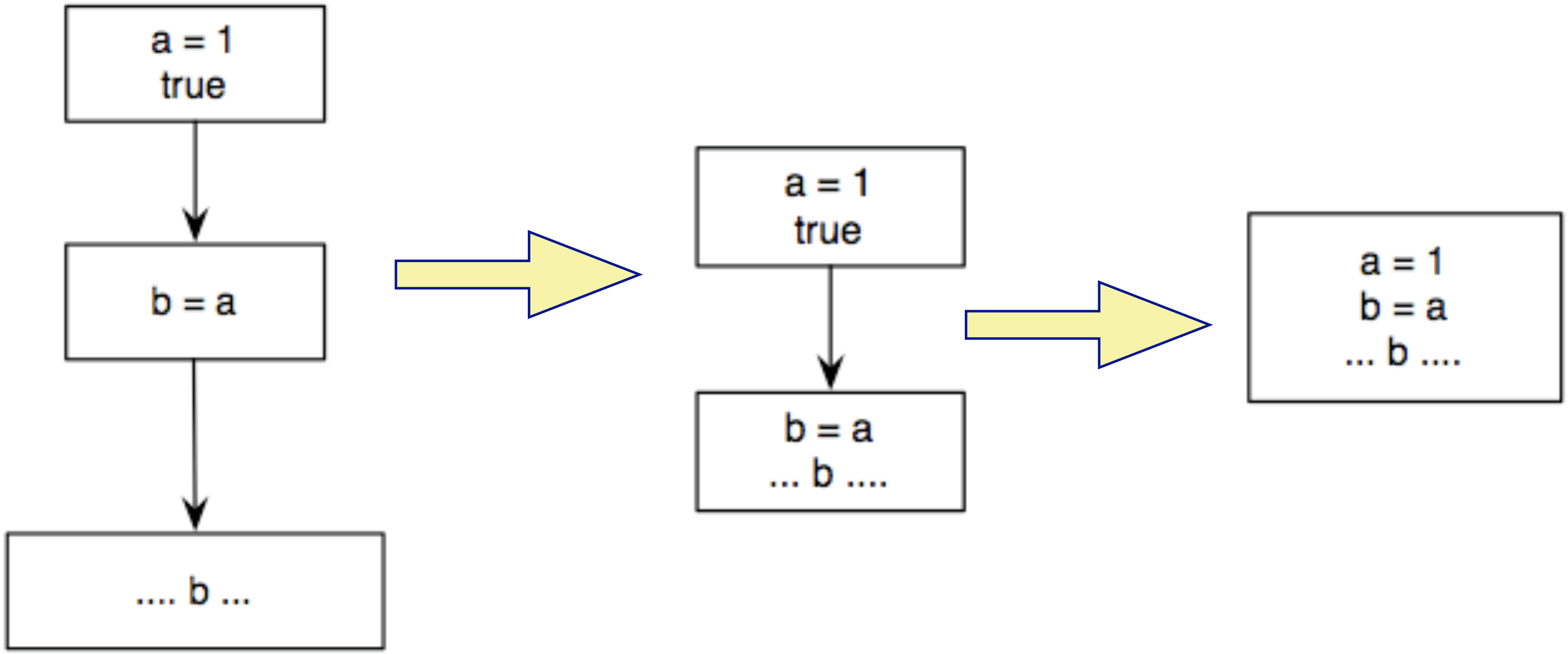
> Optimizations will degenerate CFG

> Needs to be cleaned to simplify further optimization!

Delete Empty Basic Blocks



Fuse Basic Blocks



Common Subexpression Elimination (CSE)

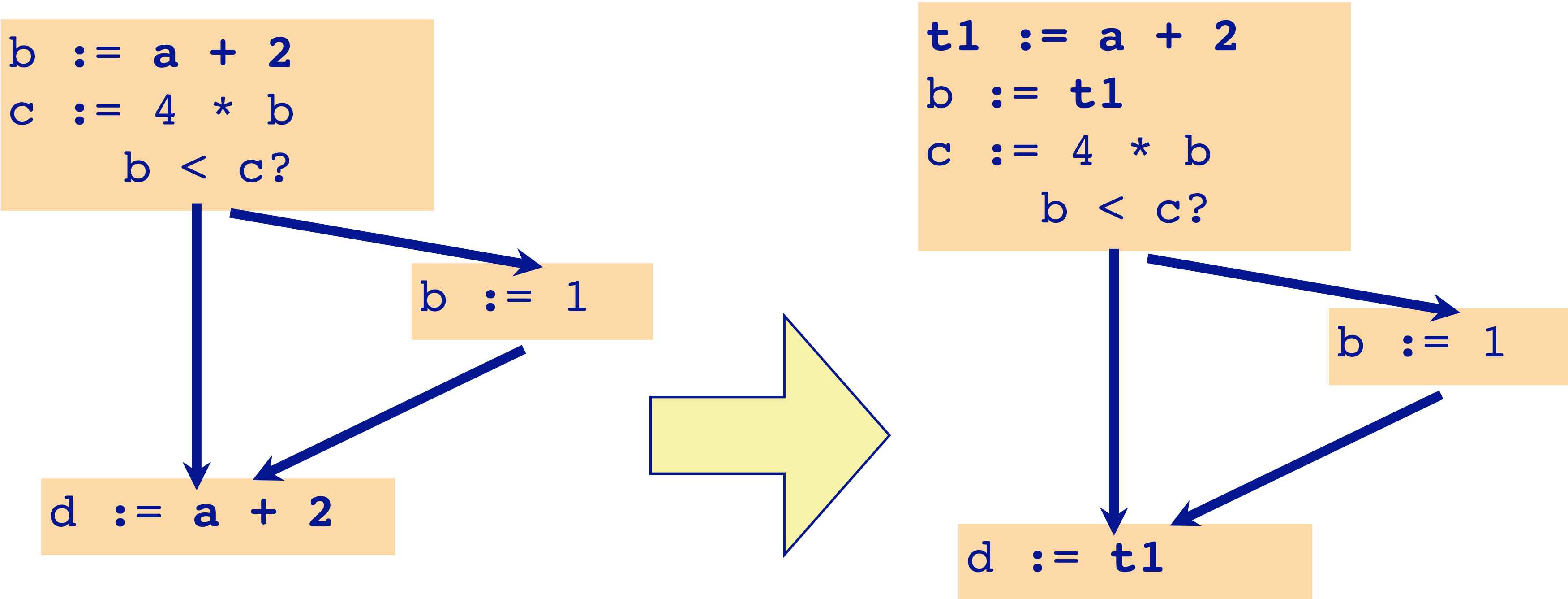
Common Subexpression:

- 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



Loop Optimizations

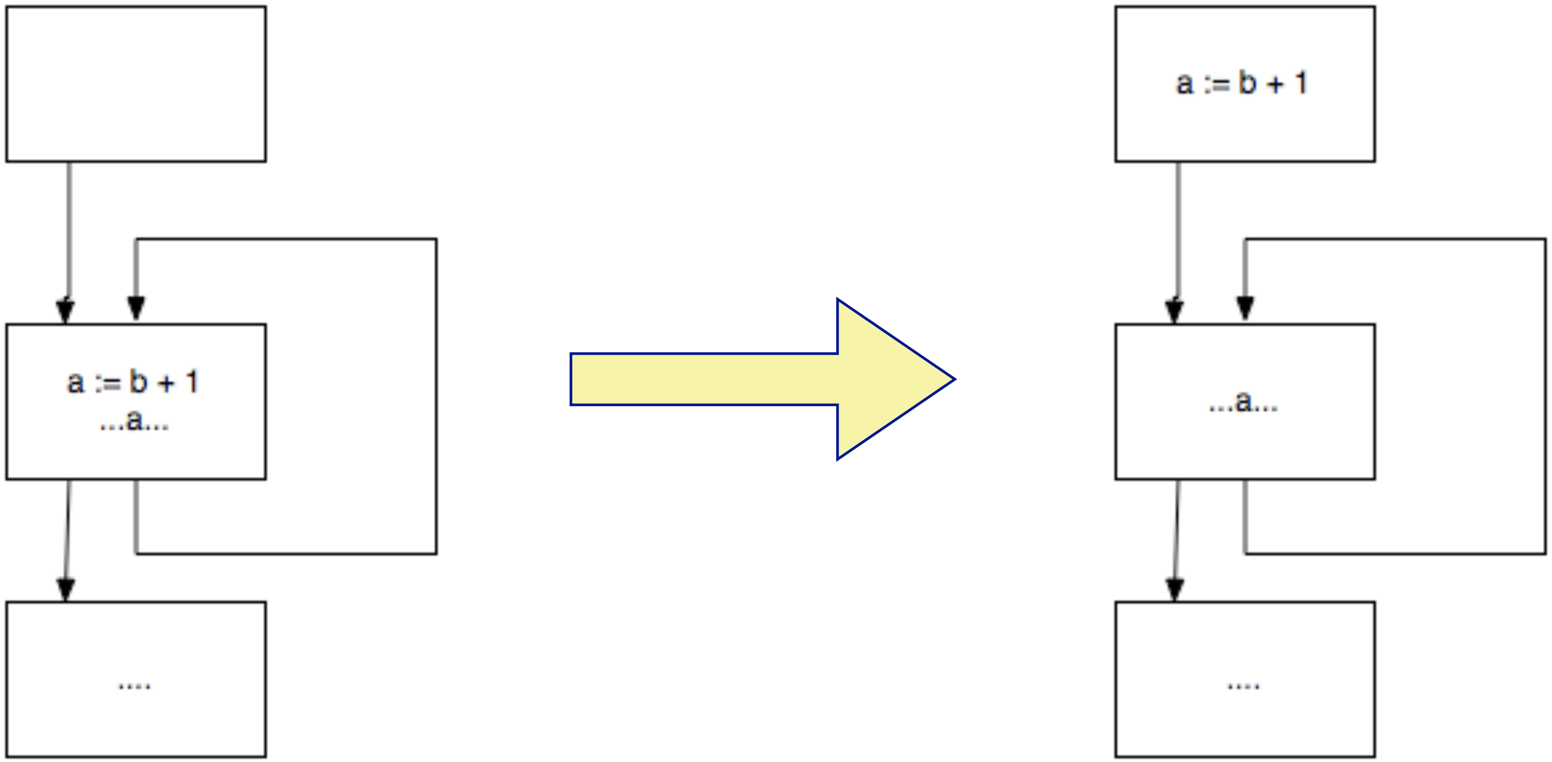
> Optimizing code in loops is important
  — often executed, large payoff

> 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
```

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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

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

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

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
c1 := 1 + b1
d1 := b1 + c1
```

```
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.

```
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!

Copy Propagation And SSA

> for a statement x1 := y1
> replace later uses of x1 with y1

```
x1 := y1
c1 := 1 + x1
d1 := x1 + c1
```

→

```
x1 := y1
c1 := 1 + y1
d1 := y1 + c1
```

Dead Code Elimination and SSA

- Variable is <u>live</u> 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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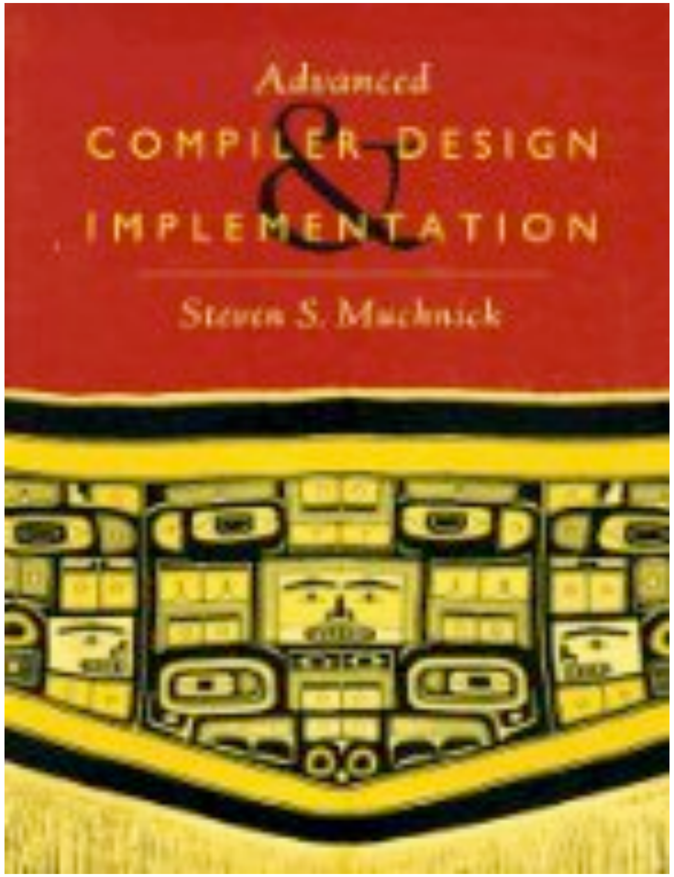
Literature

- 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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