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7. Optimization

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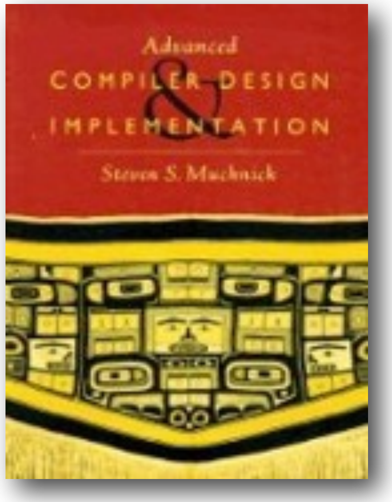
Lecture notes courtesy Marcus Denker

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*

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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**

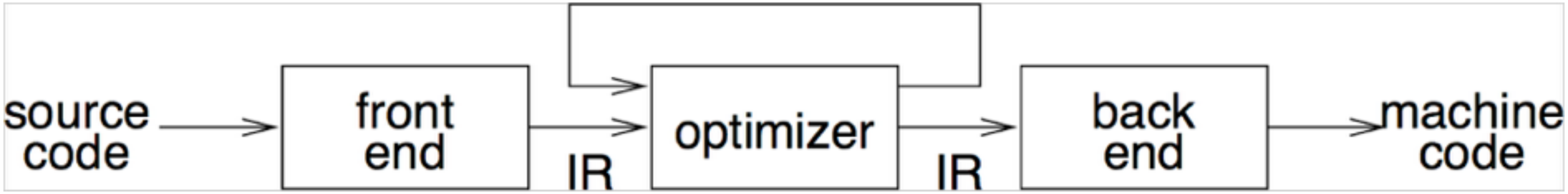
No Magic Bullet!

- 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

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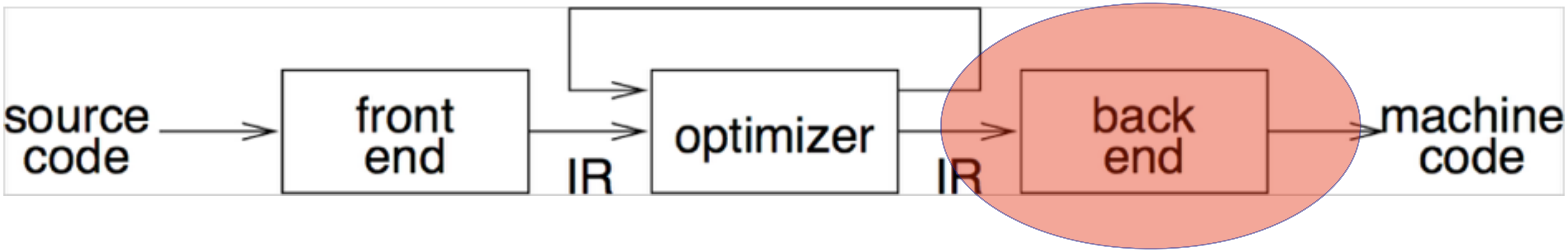
Optimizations in the Backend



- 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

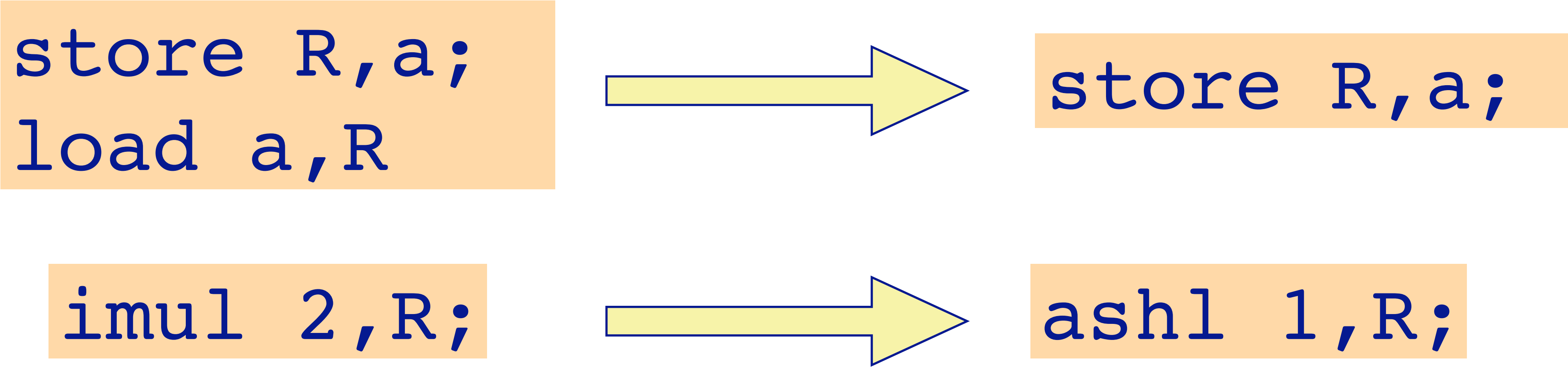
Instruction Selection

- 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
```

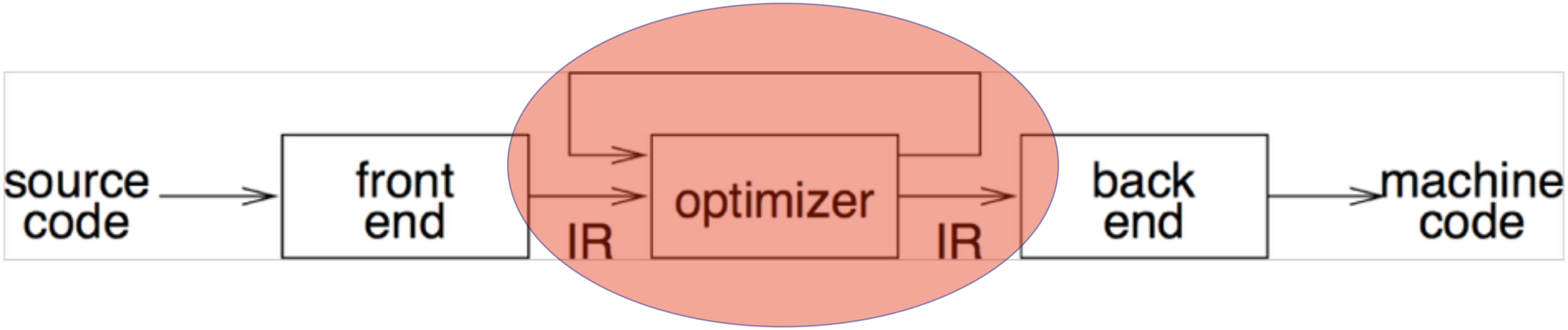
```
store R,a;
```

```
imul 2,R;
```

```
ashl 1,R;
```

Important when using simple instruction selection!

Optimization at many levels



Most optimization is done in a special phase

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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}
```

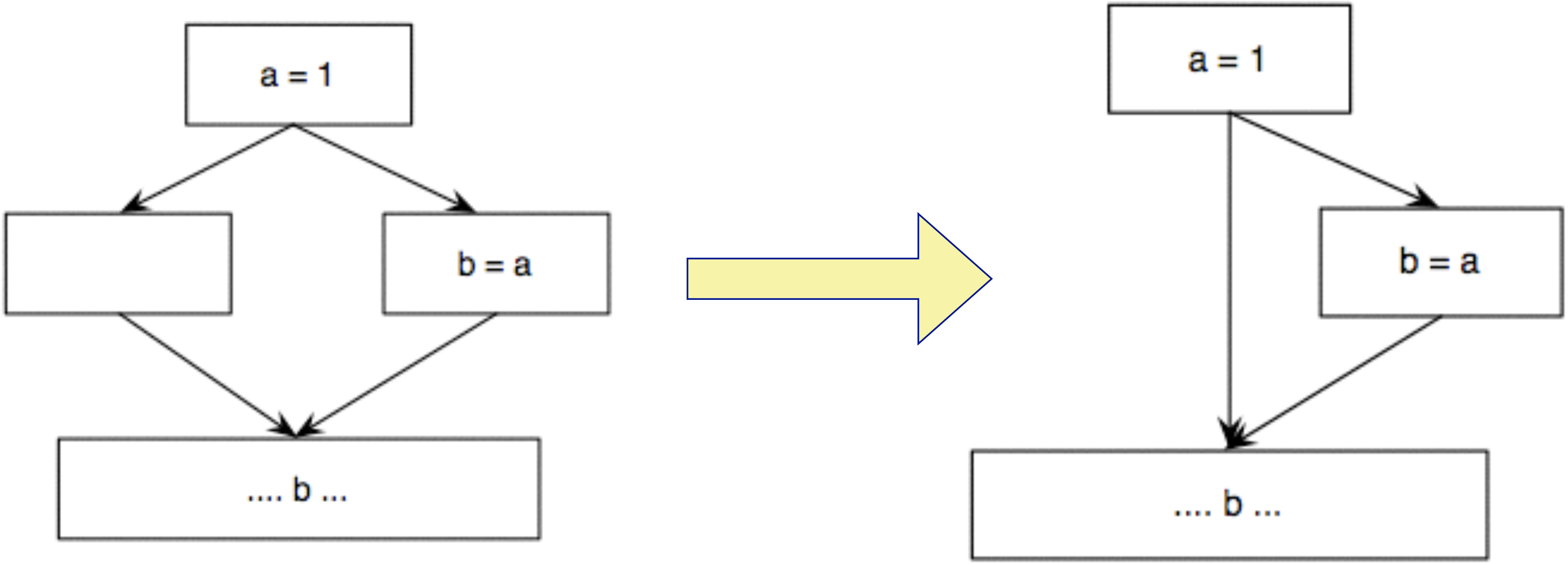
```
if (false)
{}
```

Simplify Structure

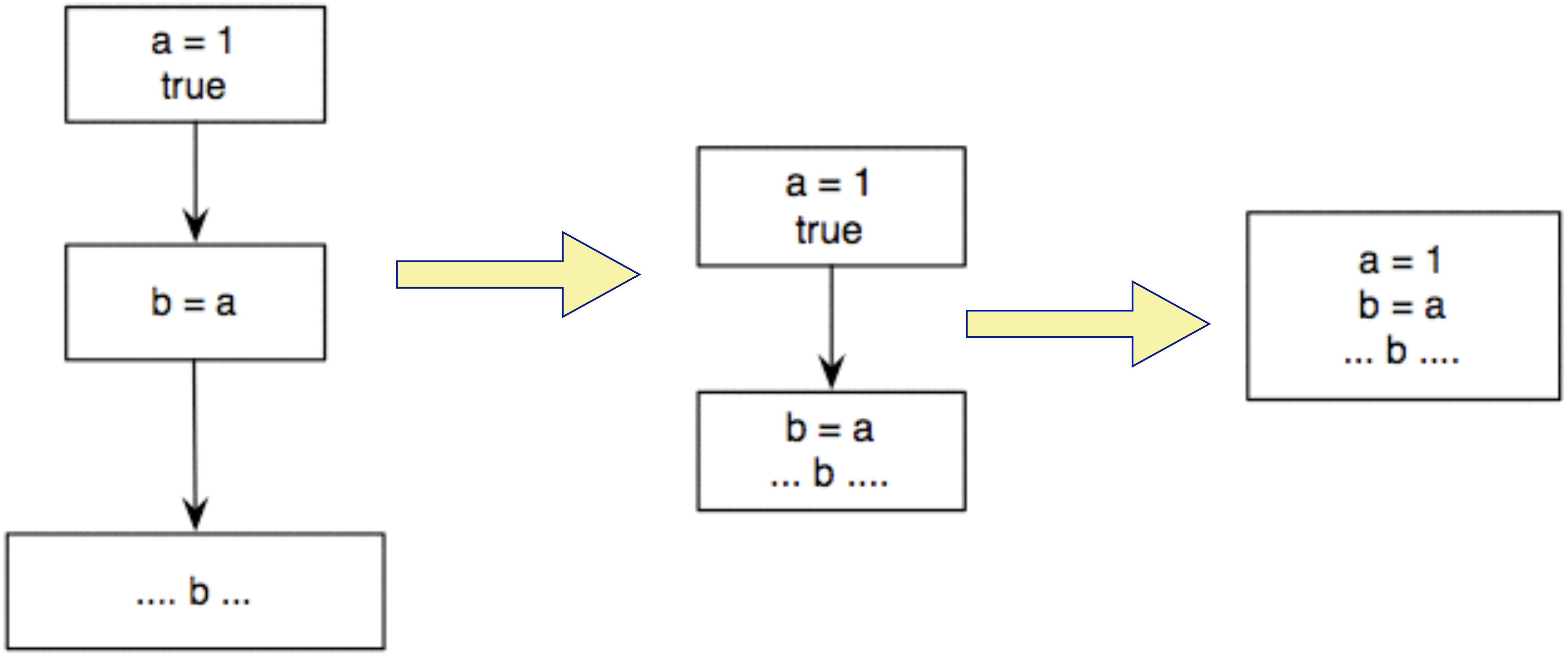
- Similar to dead code: Simplify CFG Structure
  - Eg delete empty basic blocks, fuse basic blocks (next slides)

- Optimizations will degenerate CFG
  - Needs to be cleaned to simplify further optimization!

Delete Empty Basic Blocks



Fuse Basic Blocks



a = 1
true

b = a

.... b ...

a = 1
true

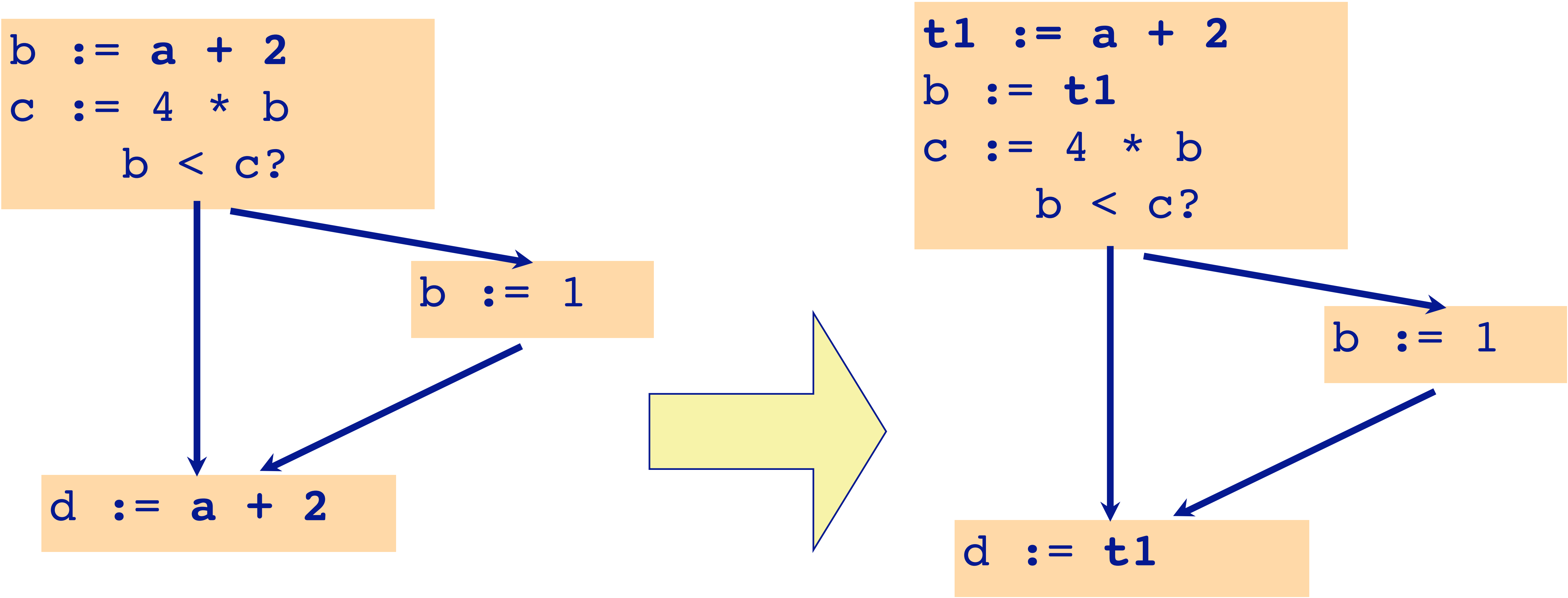
b = a
... b ....

a = 1
b = a
... b ....

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 * b
    b < c?
```

```
b := 1
```

```
d := a + 2
```

```
t1 := a + 2
b := t1
c := 4 * b
    b < c?
```

```
b := 1
```

```
d := t1
```

Loop Optimizations

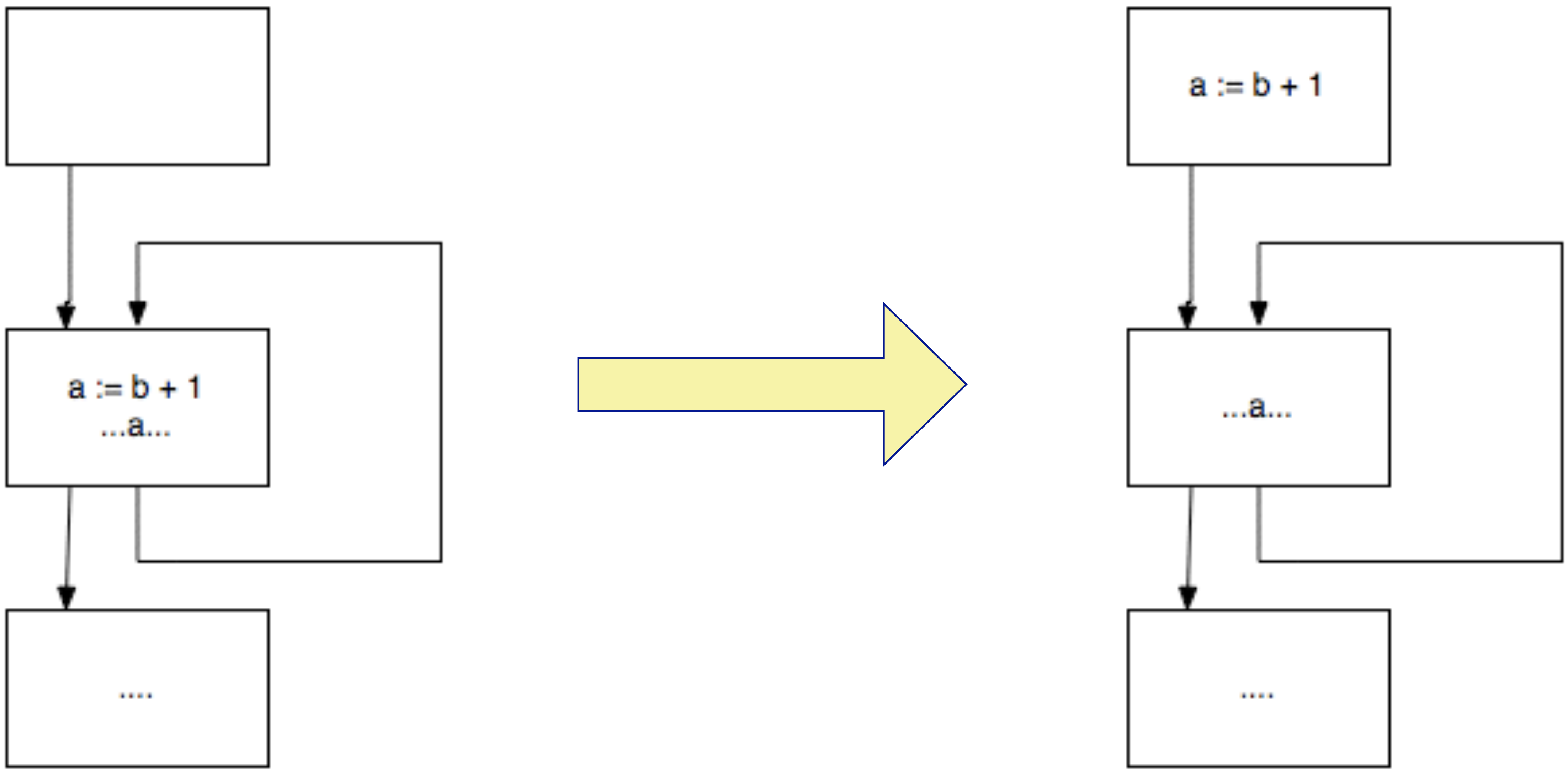
- Optimizing code in loops is important
  - often executed, large payoff

- 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;
```

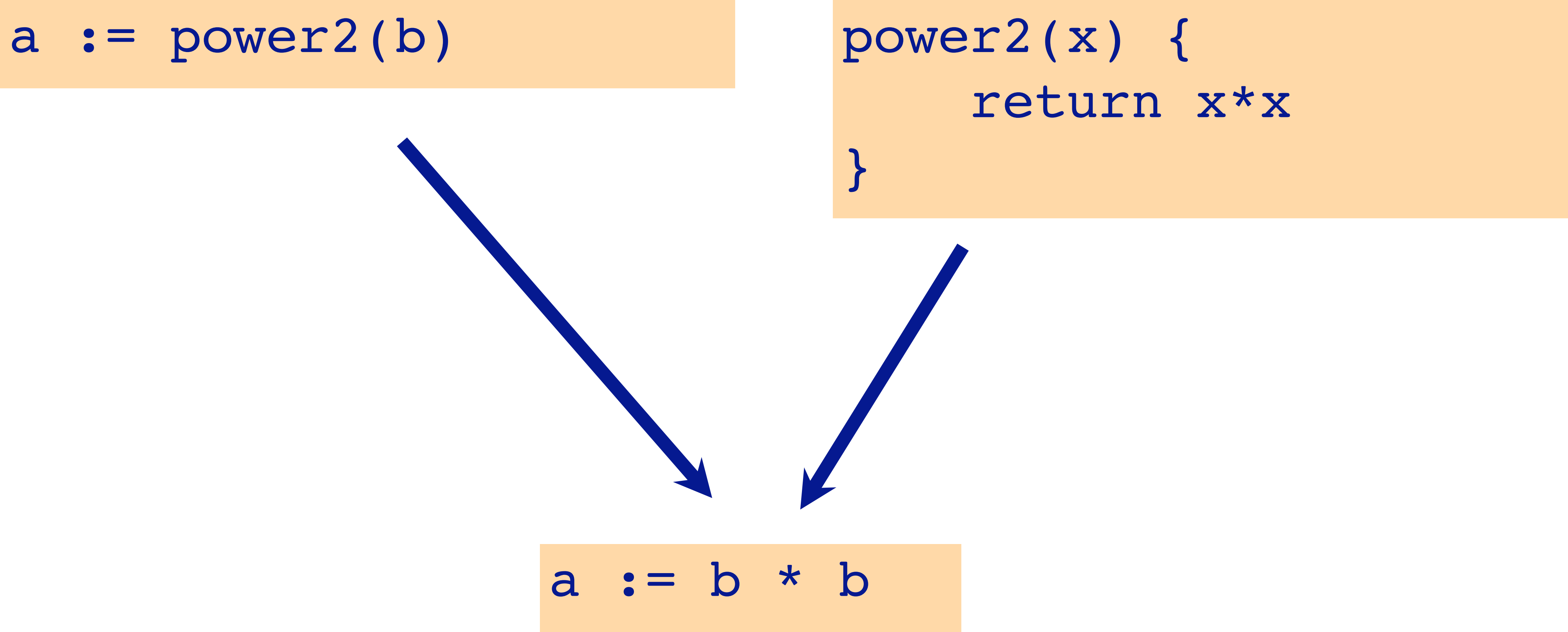
http://en.wikipedia.org/wiki/Partial_redundancy_elimination

Code Inlining

- 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

Example: Inlining



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

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

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

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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
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 + c1
```

Recall: 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 *live* if the list of uses is not empty.
- Dead definitions can be deleted
  - (If there is no side-effect)

```
b1 := 3
c1 := 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)

Multicore

- 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?*