



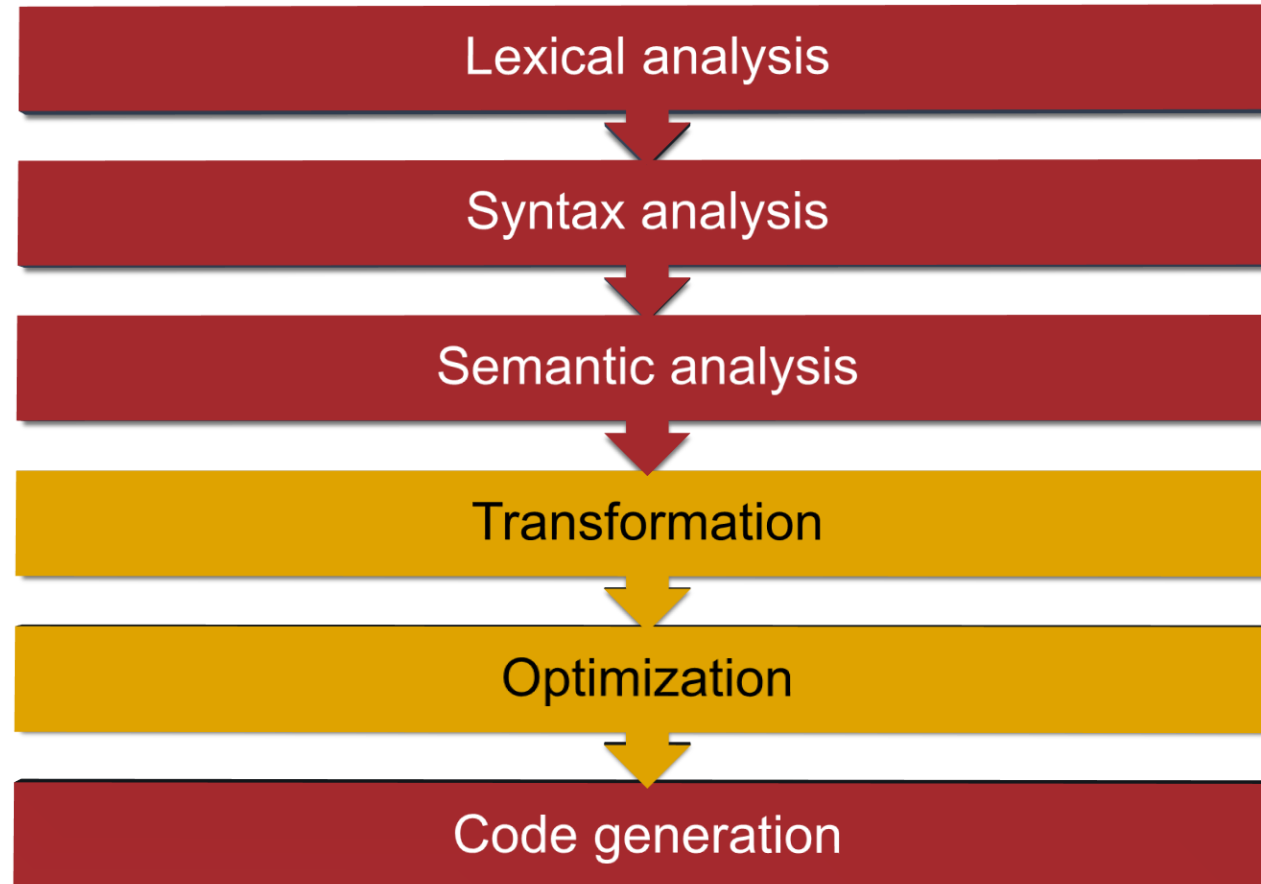
Model-based Software Development

Lecture 5

Transformation, optimization

Dr. Balázs Simon

Compilation phases



This lecture: Transformation, Optimization

I. Transformation

II. Type mapping

III. Statement mapping: SSA

IV. Optimization

V. Optimization techniques



Transformation

- Goal: map syntax tree to intermediate representation (IR)
 - > memory layout of types and data structures
 - > statements to simple operations that can be mapped to machine code directly
 - > no resource limit yet (e.g., no limit on the number of registers)
- Possible intermediate representations:
 - > 1. No explicit IR: machine code directly from syntax tree
 - > 2. Three-Address Code (TAC or 3AC): each operation has max. 3 operands (e.g., $t1 = t2 * t3$)
 - > 3. Static Single-Assignment (SSA): like TAC, but all variables are immutable

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Memory layout of simple types

■ Primitive types:

- > pointer, bool, char, byte, short, int, long, float, double, ...
- > must be aligned to addressable memory space, usually 1 byte is the minimal size
- > handle: bool values, char encoding, big/little endian, fixed/floating point, calling convention, ...

■ Enum/Flags:

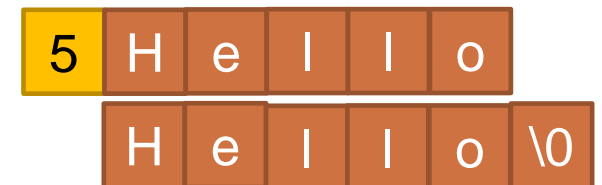
- > mapped to integral types (byte, short, int, long, ...)
- > size is dependant on the possible values, but in some languages it can be specified explicitly (e.g., C#)

■ String type:

- > primitive or composite type, depending on the language
- > simple (e.g., Pascal, C#): length + characters
- > composite (e.g., C): character array ending with '\0'

"Hello"

"Hello"



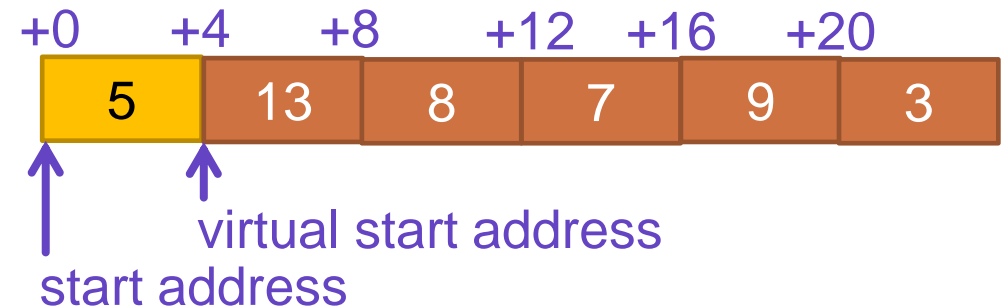
Memory layout of composite types: Array

■ Kinds:

- > static: fix size, reserved at compile time, on the stack (e.g., C)
- > dynamic: fix size, reserved at runtime, on the heap (e.g., C malloc, C#)
- > flexible: dynamic size at runtime (e.g., Python)

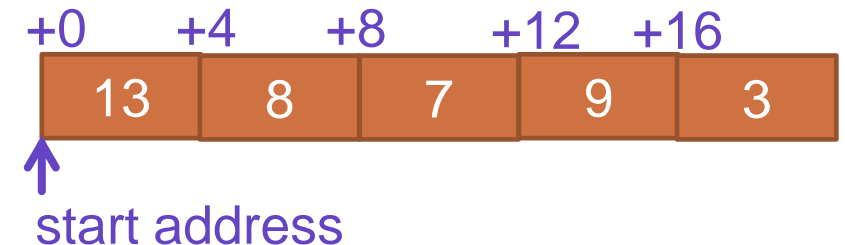
■ Checked size (e.g., C#): length + items

```
int[] a = new int[] { 13, 8, 7, 9, 3 };
```



■ Unchecked size (e.g., C): items

```
int a[] = { 13, 8, 7, 9, 3 };
```

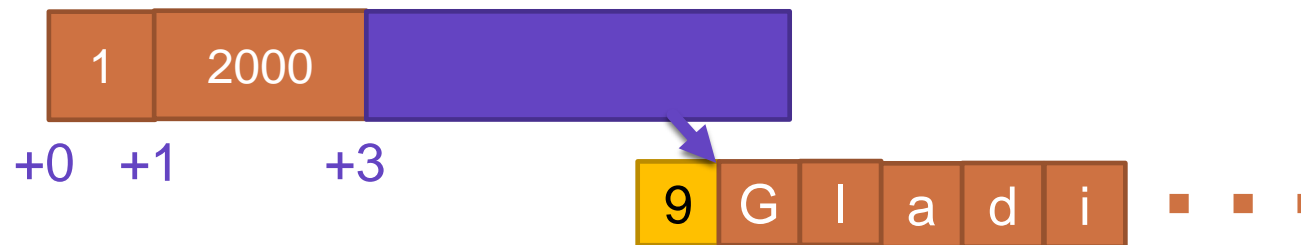


Memory layout of composite types: Struct (Union: overlapping fields)

```
var m = new Movie() { Genre = Genre.Drama, Year = 2000, Title = "Gladiator" }
```

■ Packed:

> size = sum of the sizes of the fields

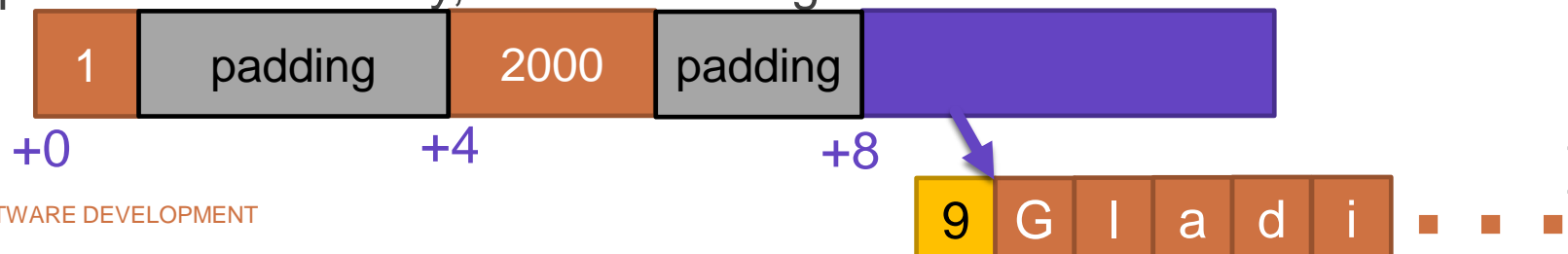


```
struct Movie
{
    Genre Genre;
    short Year;
    string Title;
}
```

■ Aligned:

> fields aligned to words

> requires more memory, but addressing is more efficient



```
enum Genre : byte
{
    Action = 0,
    Drama = 1,
    Romance = 2,
    Comedy = 3
}
```


Memory layout of composite types: Class and object

- Object: instance fields of the class stored as a struct
 - > 0th field: pointer to the type descriptor (class)
 - > the struct also contains the fields of the base classes
- Class: static fields + pointers to static and instance methods
 - > static fields: stored as a struct
 - > instance methods: implicit 0th parameter for the object (this)
 - > statikus methods: no extra parameter for the object
 - > polymorphism: virtual method table (VMT)
- Constructor:
 - > reserve object struct on the heap + initialization

Memory layout of composite types: Class and object

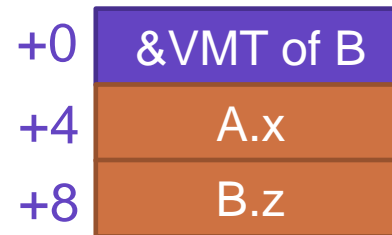
```
class A
{
    int x;
    static int y;
    void foo() { ... }
    virtual void bar() { ... }
    static void quux() { ... }
}

class B : A
{
    int z;
    static int w;
    new void foo() { ... }
    override void bar() { ... }
    virtual void garply() { ... }
}
```

Struct of an A object:



Struct of a B object :



Struct of an A class:



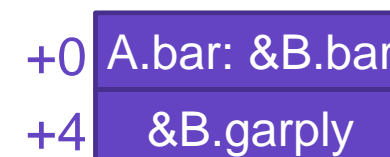
Struct of an B class :



VMT of class A:



VMT of class B:



code of A.foo

code of A.bar

code of A.quux

code of B.foo

code of B.bar

code of B.garply

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Static Single Assignment (SSA)

- Each variable gets its value exactly once
 - > at the definition, before it is used
- Notation: original variable name numbered (versioned)
- Each operation has max. 3 operands (e.g., $t1: t2 * t3$)
- Example:

Program code:

```
x = 3;  
y = 4;  
z = 5;  
x = x+y;  
z = (x+y)*z;
```



SSA code:

```
x1: 3  
y1: 4  
z1: 5  
x2: x1+y1  
t1: x2+y1  
z2: t1*z1
```

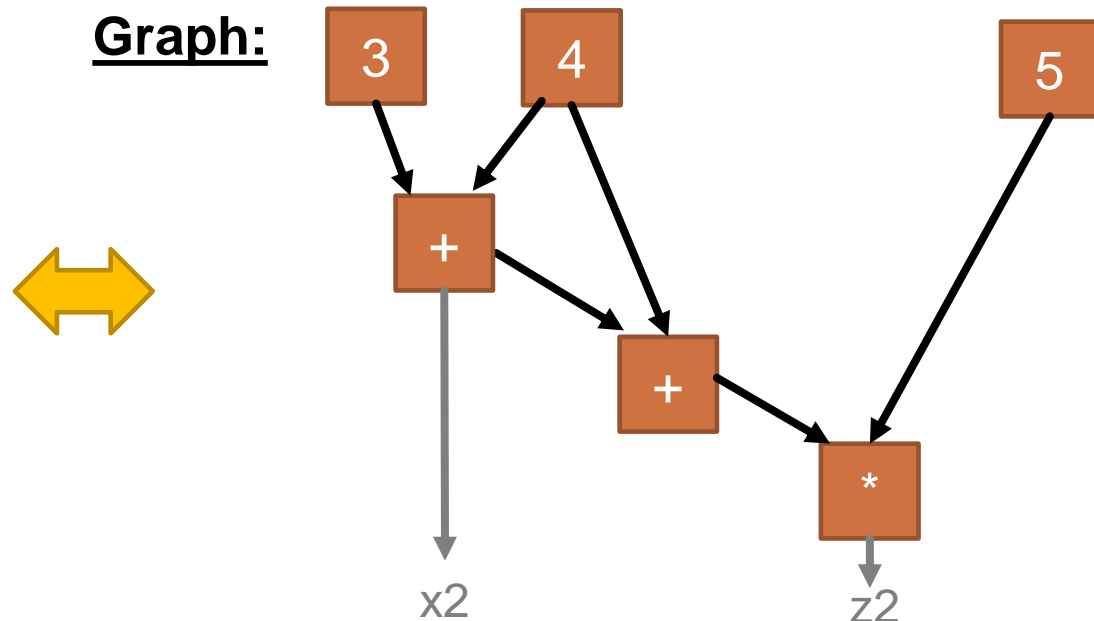
SSA graph

- Visual representation of the SSA code as a dataflow-graph (DFG)
 - > Nodes: constants or operators
 - > Directed edges: definition-use connections (reversed edges: data dependencies)
- Some optimizations are more intuitive in graph form

SSA code:

```
x1: 3  
y1: 4  
z1: 5  
x2: x1+y1  
t1: x2+y1  
z2: t1*z1
```


Graph:



Φ -function

Question: what happens when multiple control flows meet?

```
if (x < y) z = x;  
else z = y;  
w = z;
```




```
if (x1 < y1) z1 = x1;  
else z2 = y1;  
w1 = ???
```

A special notation is needed: Φ -function

Value: the parameter corresponding to the actual control branch.

```
if (x < y) z = x;  
else z = y;  
w = z;
```



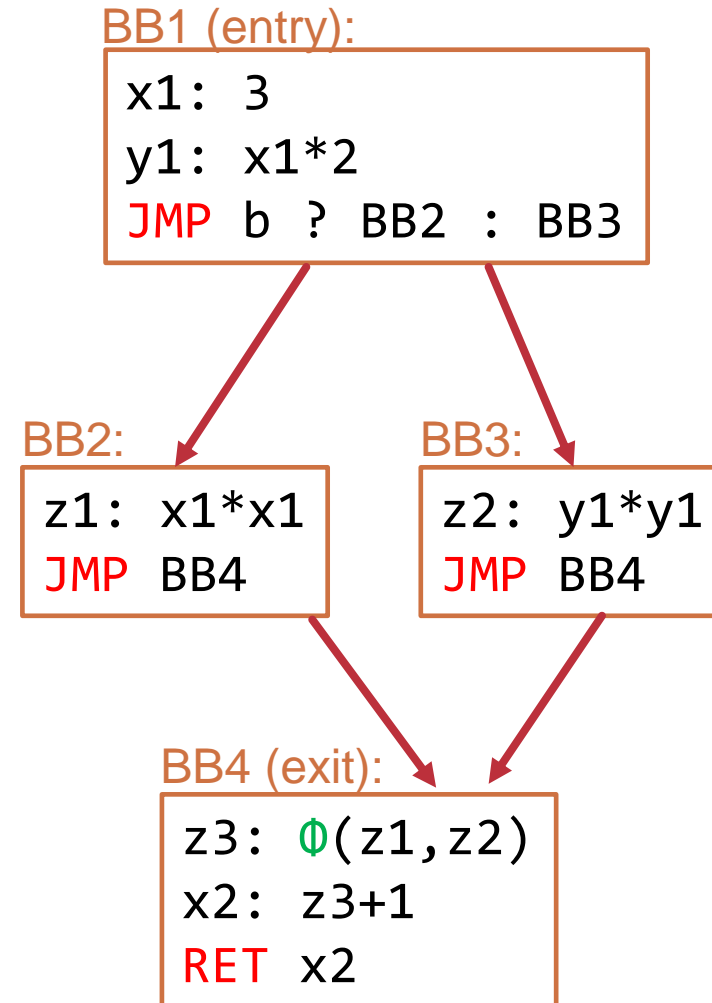
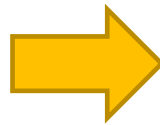
```
if (x1 < y1) z1 = x1;  
else z2 = y1;  
z3 =  $\Phi$ (z1, z2);  
w1 = z3;
```

Mapping of the program code

- Whole program: split into functions
- Function: control-flow graph (CFG)
 - > node: basic block
 - > edge: jump from one block to another
 - > two special blocks: entry block and exit block
- Basic block:
 - > statement series of maximum length (SSA statements)
 - > atomic: if one statement is executed in a block, then all other statements within the block are executed, too
 - > starts with a label, does not contain any other labels
 - > ends with a jump to a label or with a conditional jump to a label, contains no other jumps (calling another function is not a jump)

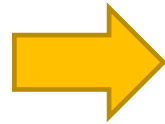
Control-flow graph example

```
int foo(bool b)
{
    int x = 3;
    int y = x*2;
    int z;
    if (b) z = x*x;
    else z = y*y;
    x = z+1;
    return x;
}
```

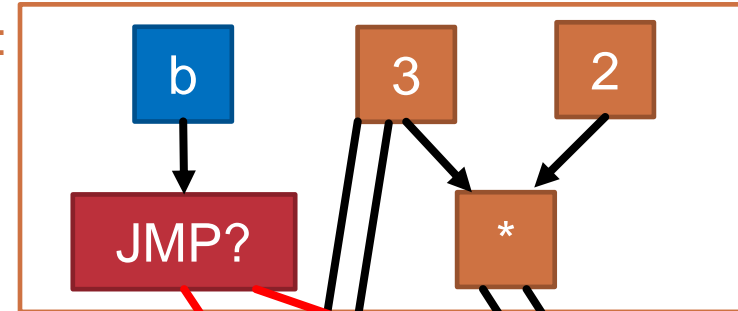


Control-flow and data-flow graphs

```
int foo(bool b)
{
    int x = 3;
    int y = x*2;
    int z;
    if (b) z = x*x;
    else z = y*y;
    x = z+1;
    return x;
}
```



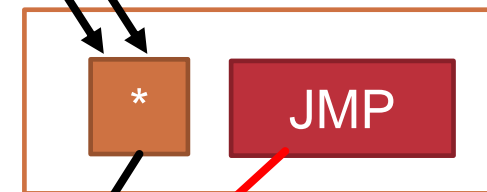
BB1 (entry):



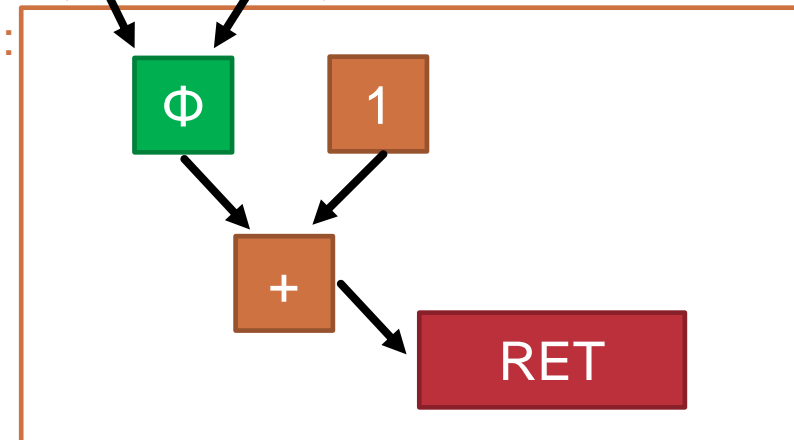
BB2:



BB3:



BB4 (exit):



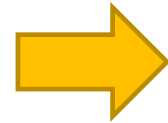
Mapping of statements

- Arithmetic and logical expressions: mapped as is
 - > some languages require overflow checking (expensive!)
- Branches, loops, exceptions: basic blocks and control edges
- Memory access: pointer arithmetics (base address + relative address)
 - > read, write
 - > some languages require index checking (expensive!)
- Type conversion: mapped to the corresponding operations
- Function call:
 - > save state, reserve stack, pass control, free stack, restore state

Arithmetic and logical expressions

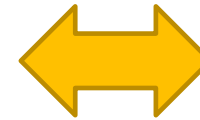
Program code:

```
bool foo(int y)
{
    return 3 * y + 4 > 7;
}
```

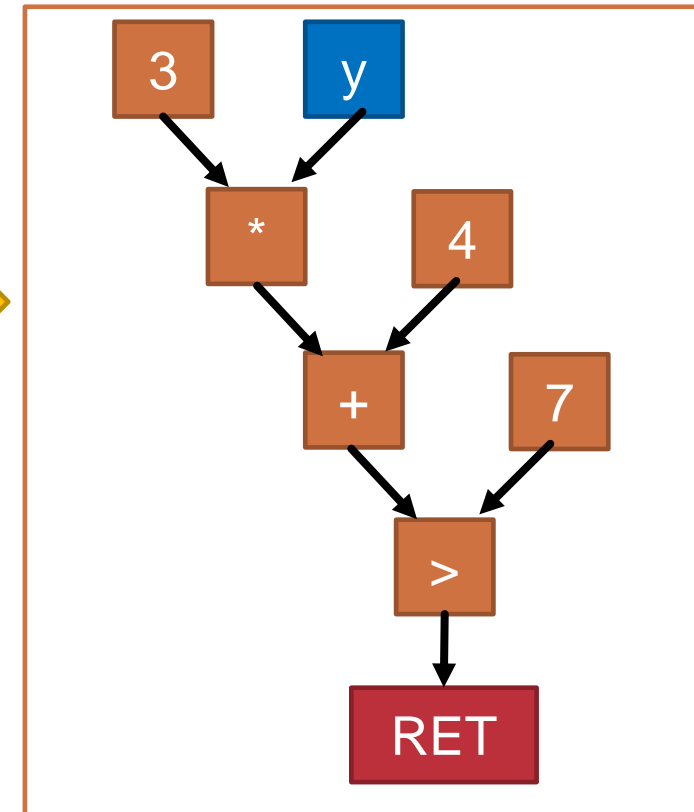


SSA:

```
t1: 3 * y
t2: t1 + 4
t3: t2 > 7
RET t3
```



Graph:

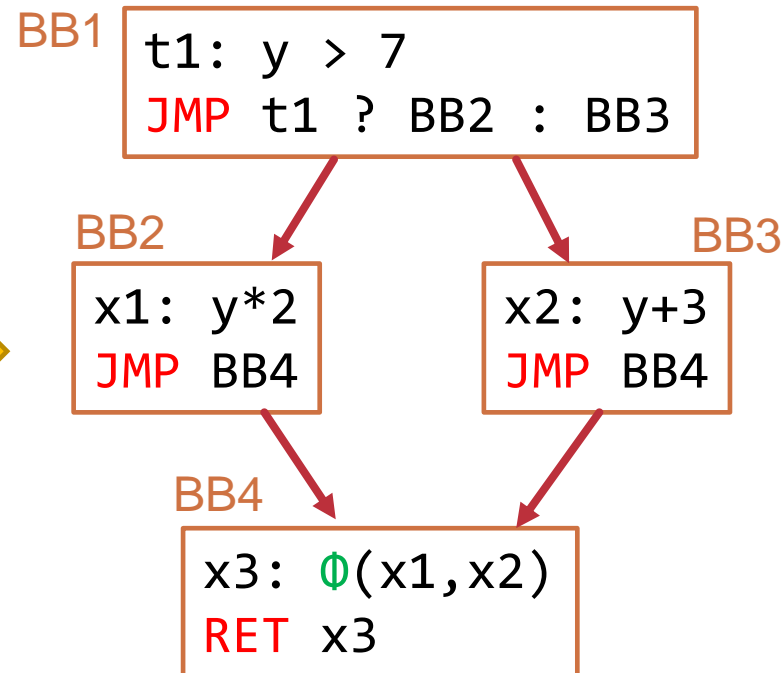


Branching: if

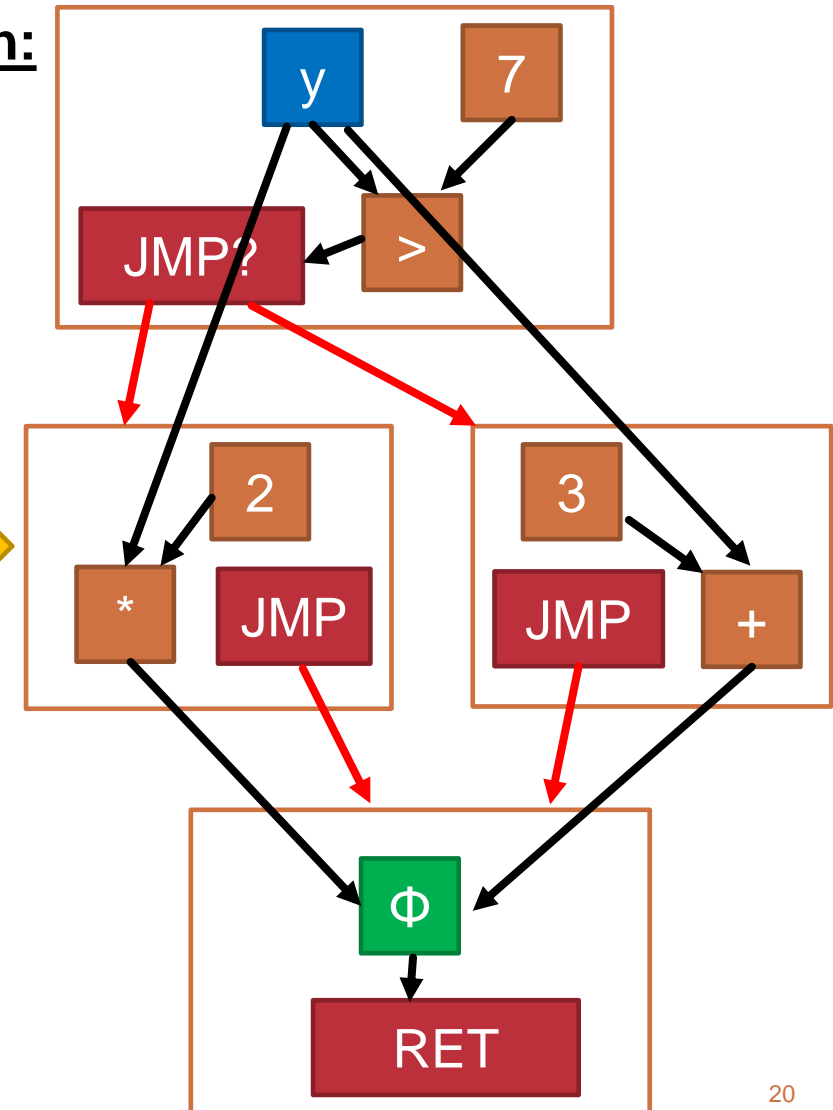
Program code:

```
int foo(int y)
{
    int x;
    if (y > 7)
    {
        x = y*2;
    }
    else
    {
        x = y+3;
    }
    return x;
}
```

SSA:



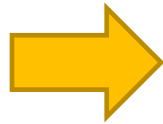
Graph:



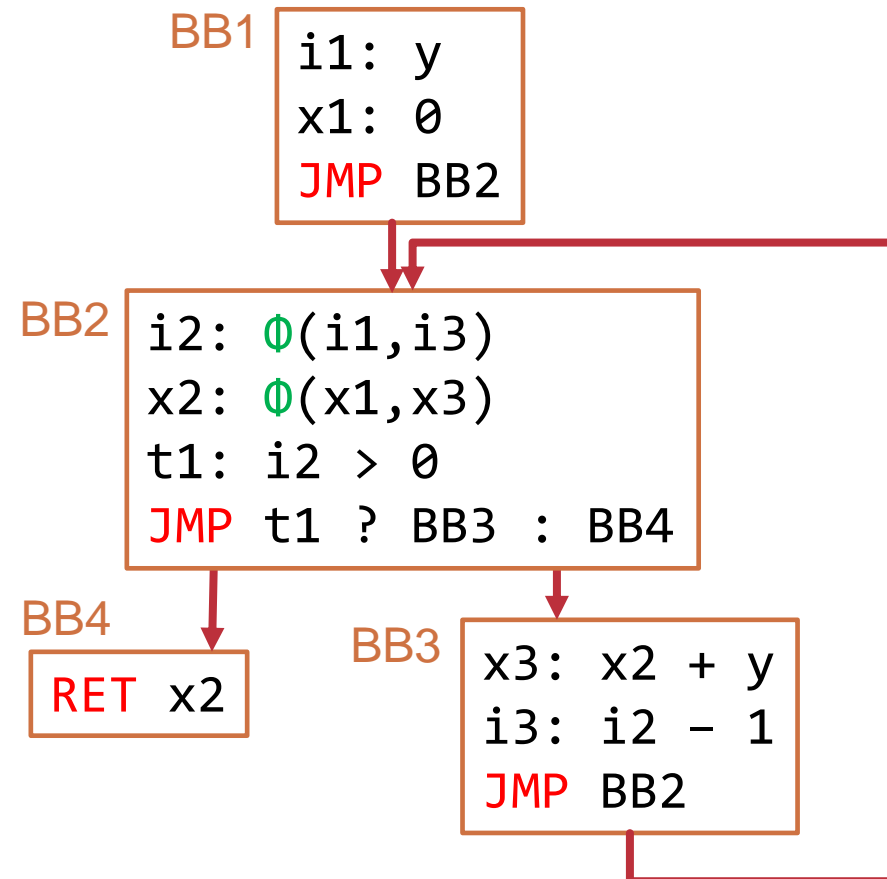
Loop: while

Program code:

```
int foo(int y)
{
    int i = y;
    int x = 0;
    while (i > 0)
    {
        x += y;
        --i;
    }
    return x;
}
```



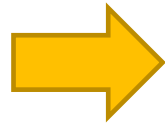
SSA:



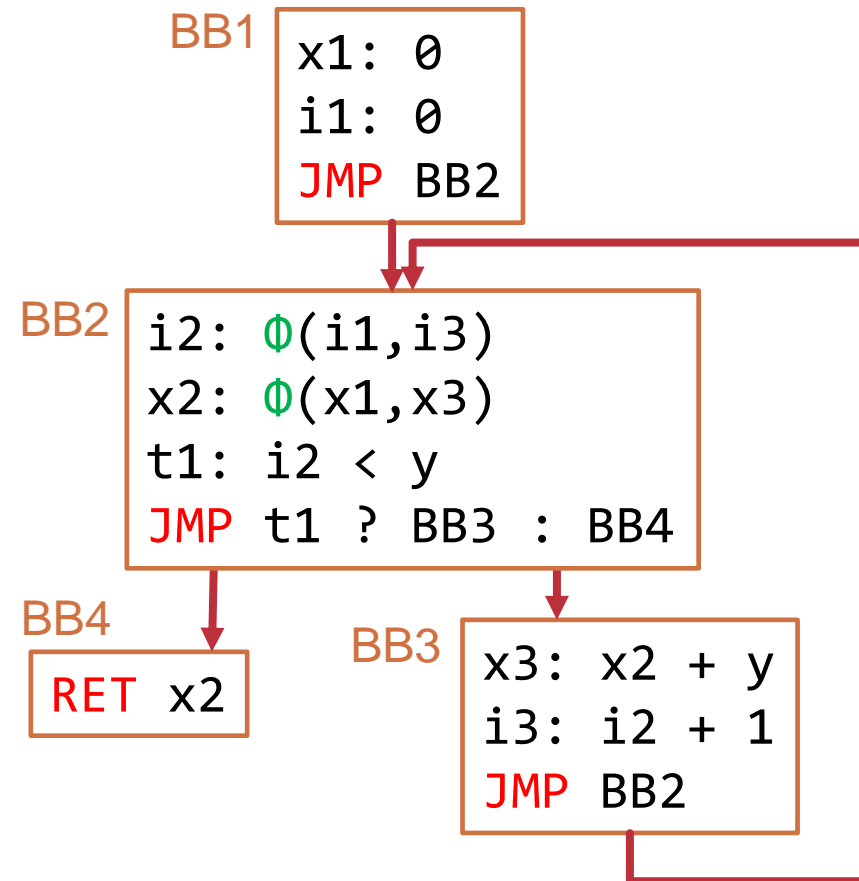
Loop: for

Program code:

```
int foo(int y)
{
    int x = 0;
    for (int i = 0; i < y; ++i)
    {
        x += y;
    }
    return x;
}
```



SSA:

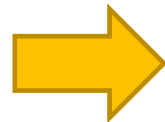


Memory: read (LD = load), write (ST = store)

Address: base + offset

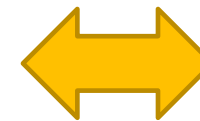
Program code:

```
class P { int Q; int R; }  
void foo(P p, int[] a)  
{  
    int q = p.Q;  
    int r = p.R;  
    int s = a[2];  
    p.R = s;  
    a[2] = q;  
}
```

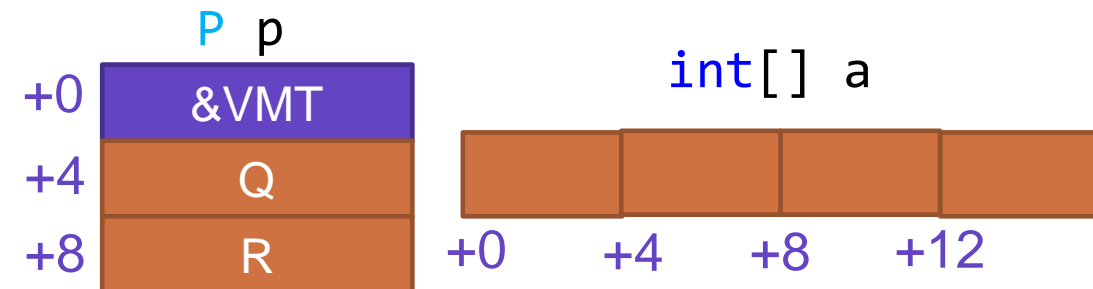
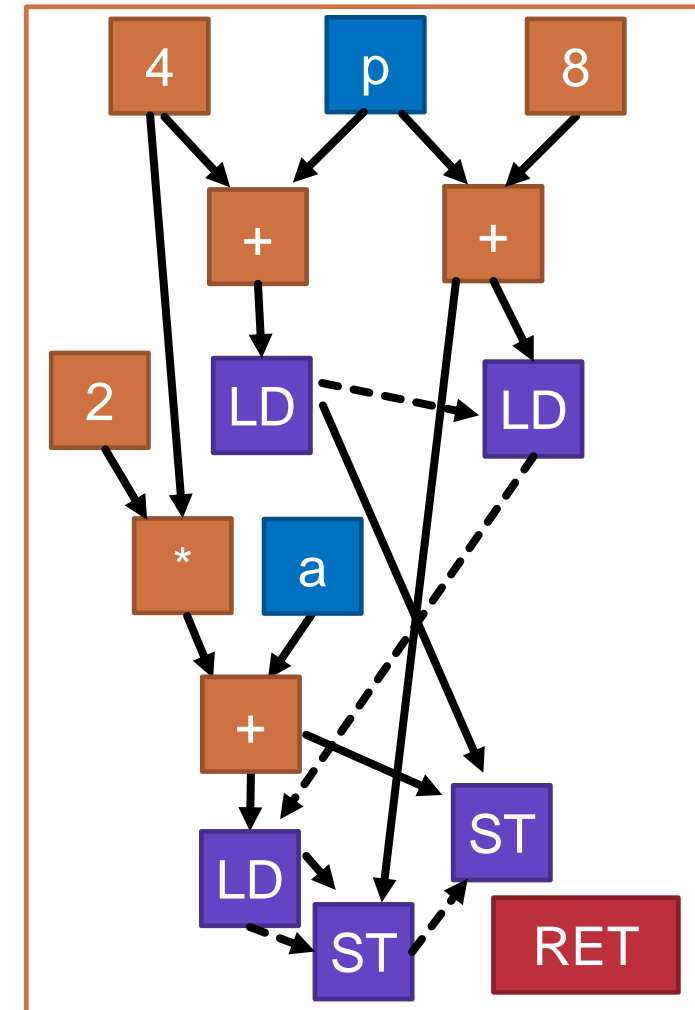


SSA:

```
t1: p + 4  
q1: LD t1  
t2: p + 8  
r1: LD t2  
t3: 4 * 2  
t4: a + t3  
s1: LD t4  
ST t2: s1  
ST t4: q1  
RET
```



Graph:



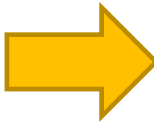
Function call

Program code:

```
bool foo(int y)
{
    return bar(y+1)-3;
}
```

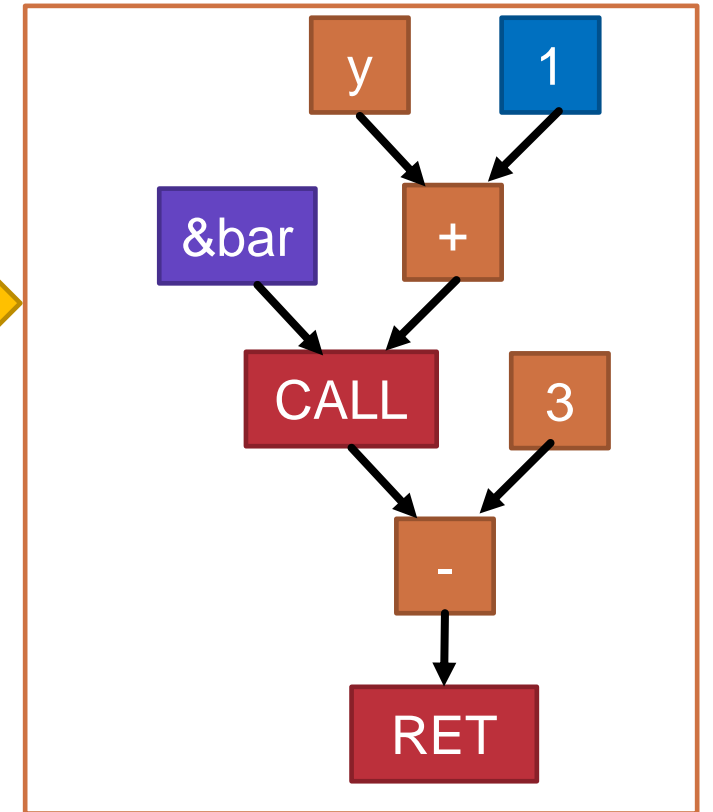
```
int bar(int x)
{
    return x*2;
}
```

SSA:



```
t1: y + 1
t2: CALL bar(t1)
t3: t2 - 3
RET t3
```

Graph:



Function call

- 1. Save state (registers)
- 2. Reserve stack for the function (Stack Frame)
 - > return address, return value, parameters, local variables
- 3. Write return address to stack (there are 2 return addresses if there is exception handling!)
- 4. Write arguments to the stack
- 5. Set Program Counter to the address of the function
- 6. Execute the body of the function
- 7. Reset Program Counter to the return address
- 8. Read return value from the stack
- 9. Free the reserved Stack Frame
- 10. Restore state (registers)

SSA computation

- Create basic blocks and the control flow graph
- For each block: number the values for each statement/expression
- Φ -functions can only be computed, when all preceding blocks are finished
 - > until then: temporary Φ' function
- Φ -function can be inserted into a preceding block, too!
- A Φ' function may not necessarily result in a Φ -function

Rules for the Φ -function

- Φ -functions always appear at the beginning of a basic block which has multiple preceding blocks
- A Φ -function has exactly as many operands as the number of preceding basic blocks
- The value of the Φ -function is the value of the operand coming from the actual preceding block at runtime
- All Φ -functions must be evaluated simultaneously inside a single block

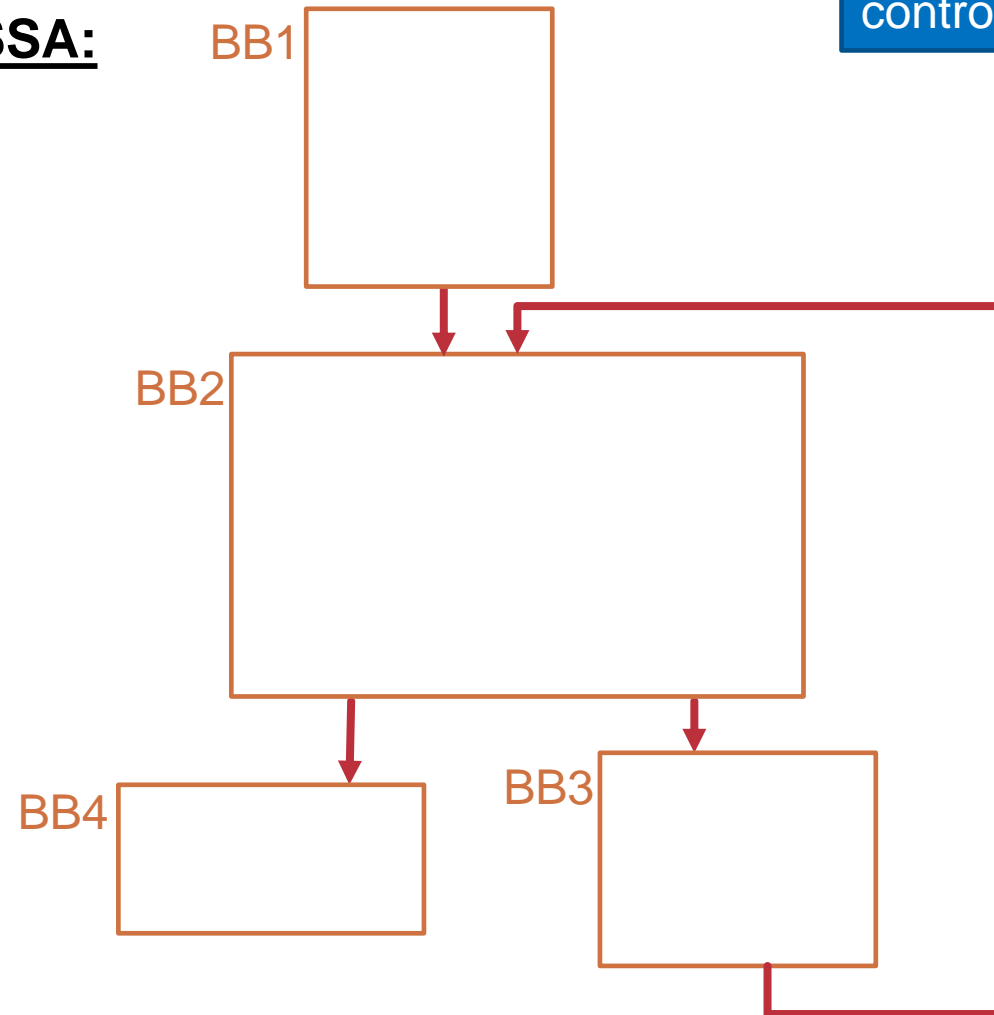
SSA computation example (1/6)

Create basic blocks and control-flow graph.

Program code:

```
int foo(int y)
{
    int x = 0;
    int z = 2;
    for (int i = 0; i < y; ++i)
    {
        x += y;
    }
    return x + z;
}
```

SSA:

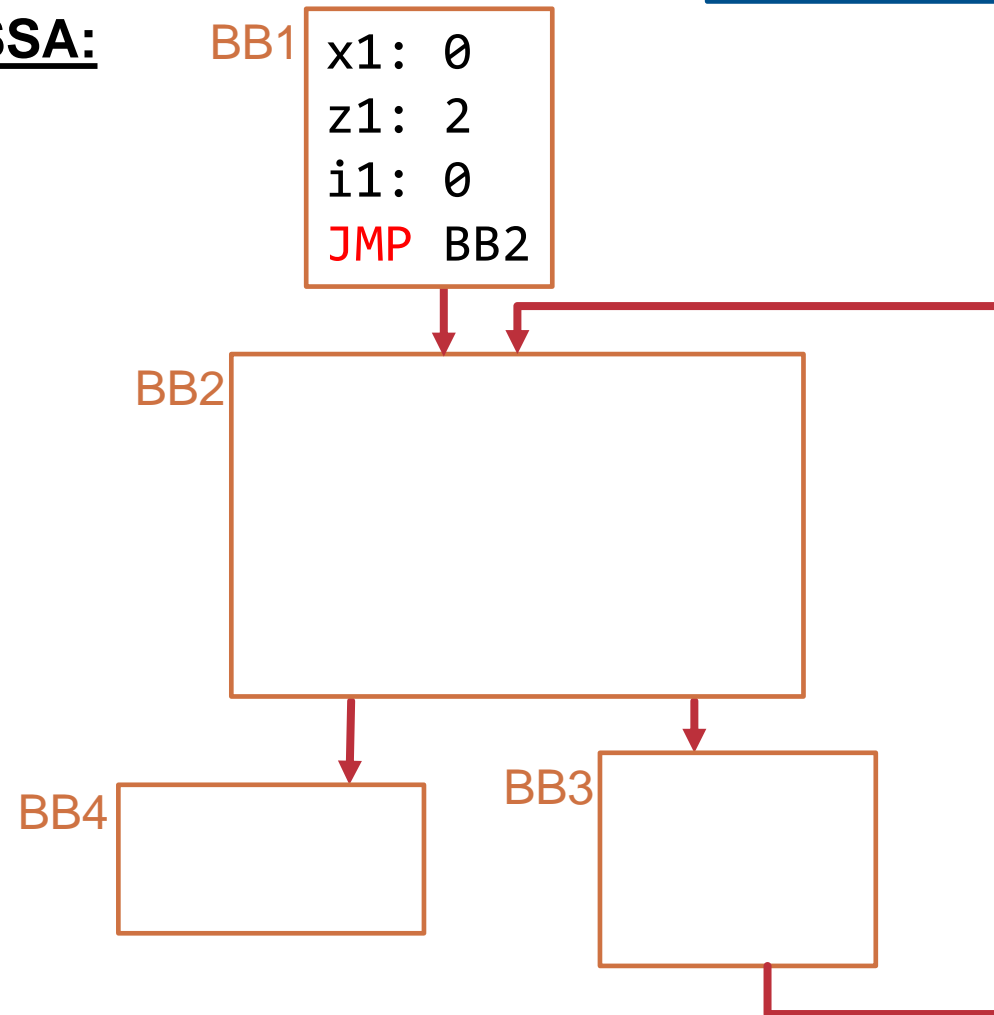


SSA computation example (2/6)

Program code:

```
int foo(int y)
{
    int x = 0;
    int z = 2;
    for (int i = 0; i < y; ++i)
    {
        x += y;
    }
    return x + z;
}
```

SSA:



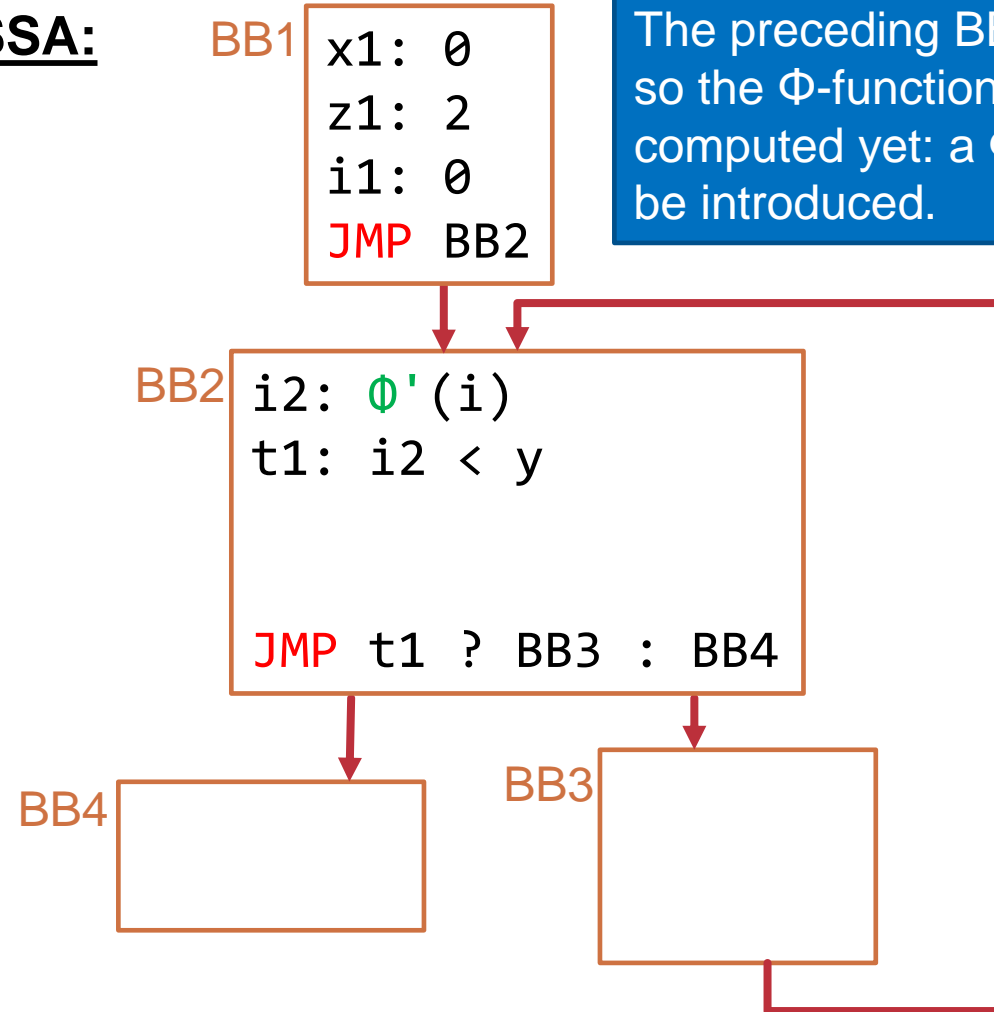
Number values in BB1.

SSA computation example (3/6)

Program code:

```
int foo(int y)
{
    int x = 0;
    int z = 2;
    for (int i = 0; i < y; ++i)
    {
        x += y;
    }
    return x + z;
}
```

SSA:



Number values in BB2.

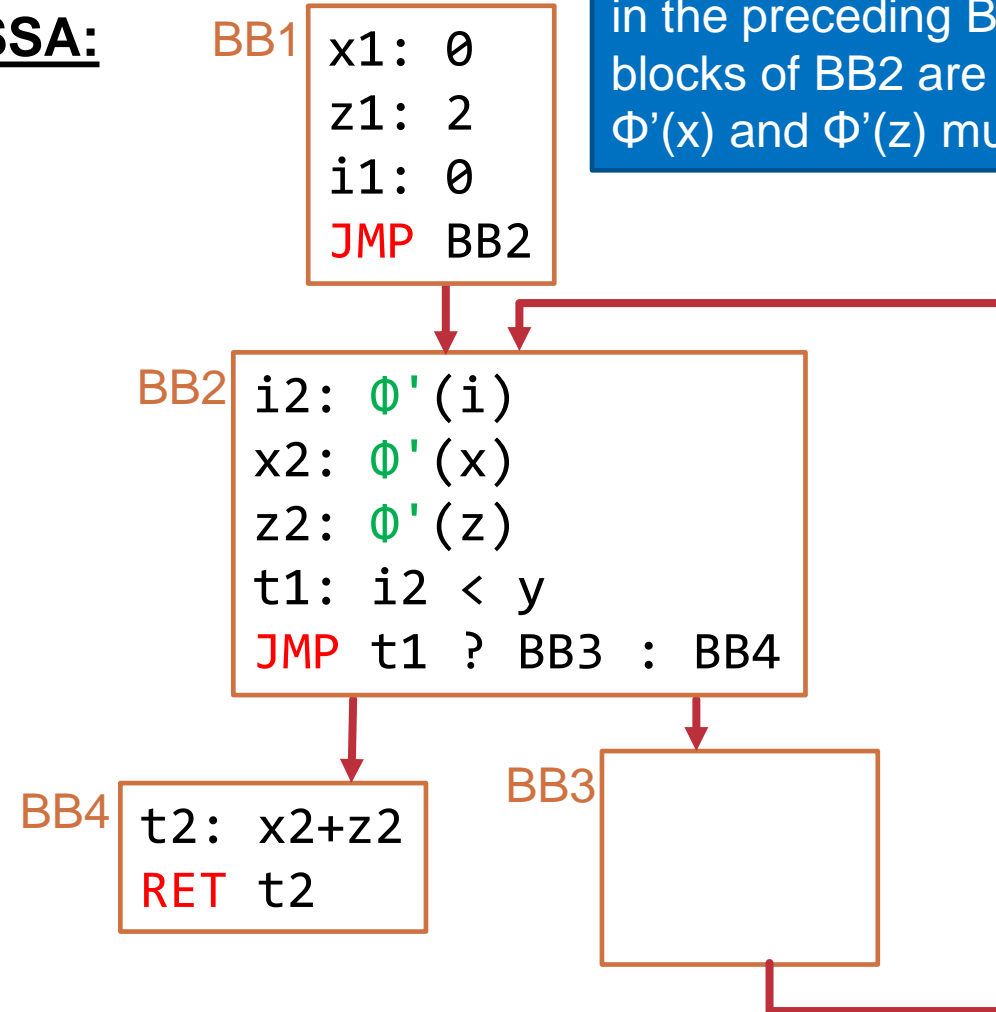
The preceding BB3 is not yet finished, so the Φ -function of i cannot be computed yet: a $\Phi'(i)$ function must be introduced.

SSA computation example (4/6)

Program code:

```
int foo(int y)
{
    int x = 0;
    int z = 2;
    for (int i = 0; i < y; ++i)
    {
        x += y;
    }
    return x + z;
}
```

SSA:



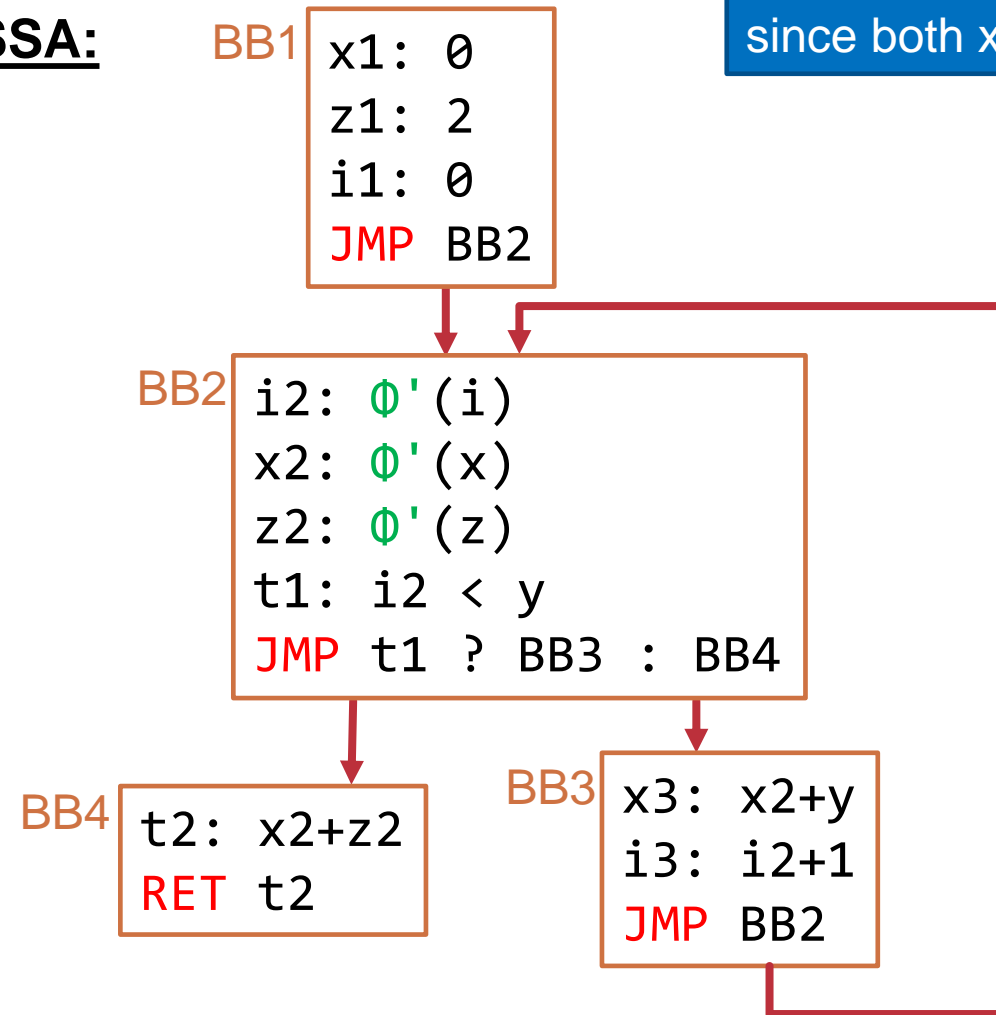
BB4 uses `x` and `z`. They don't appear in the preceding BB2. The preceding blocks of BB2 are not yet finished: $\Phi'(x)$ and $\Phi'(z)$ must be introduced.

SSA computation example (5/6)

Program code:

```
int foo(int y)
{
    int x = 0;
    int z = 2;
    for (int i = 0; i < y; ++i)
    {
        x += y;
    }
    return x + z;
}
```

SSA:



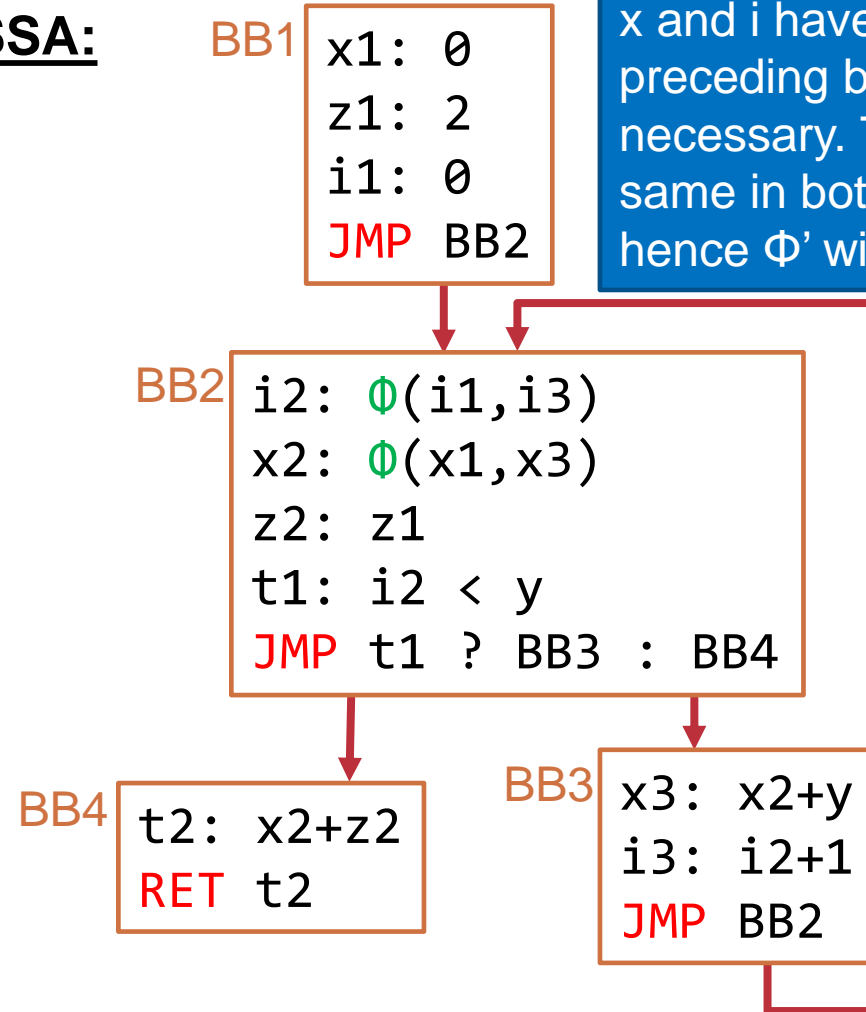
BB3 can be computed easily,
since both x and i appear in BB2.

SSA computation example (6/6)

Program code:

```
int foo(int y)
{
    int x = 0;
    int z = 2;
    for (int i = 0; i < y; ++i)
    {
        x += y;
    }
    return x + z;
}
```

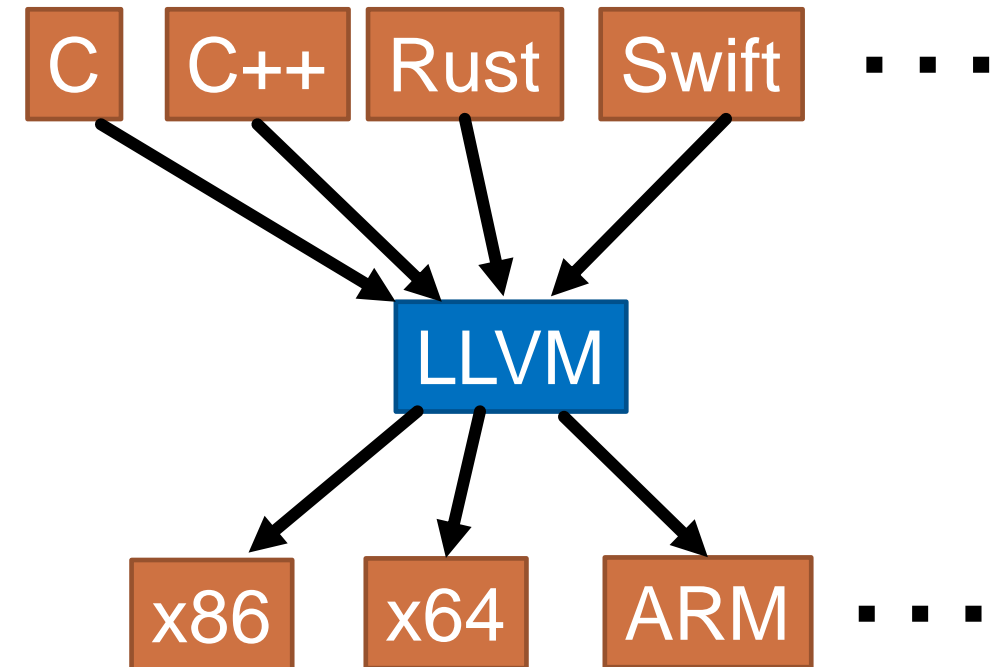
SSA:



Transformation of Φ' in BB2:
x and i have different numbers in the preceding blocks, the Φ -function is necessary. The numbers of z are the same in both preceding blocks, hence Φ' will not lead to a Φ -function.

LLVM

- Compiler tool
 - > front end (transformation into SSA form)
 - > optimization
 - > back end (machine code generation)
- LLVM Intermediate Representation (IR) independent of programming languages
 - > type system, statements and expressions
- We can use it for our own compiler!
- Alternative for LLVM:
 - > we can generate C, Java, C#, etc. code, and compile it with the regular compiler



This lecture: Transformation, Optimization

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Optimization

- Goal: more efficient execution without changing the observable behavior
 - > smaller code, faster execution, less memory, lower consumption, etc.
- There is no optimal program, only optimized!
 - > otherwise, we would have an algorithm for the undecidable halting problem
- Some examples for optimization techniques:
 - > Compile time evaluation of constant expressions, Dead code elimination, Operator simplification, Moving loop-invariant code, Eliminating partial redundancies, Moving code, Elimination of index checking, Inlining functions, Simplification of execution branches, Loop unrolling/splitting, Register assignment, Replace right recursion with loop

Optimization order

- Question: Which optimizations to apply? In what order?
 - > no exact answer
- Some optimizations are similar to each other, or subsets of each other
- For numerical programs:
 - > operator simplification: usually results in at least 2x faster code
 - > cache optimization: usually results in at least 2-5x faster code
- Other optimizations:
 - > first optimization usually results in 15% faster code
 - > each further optimization brings less than 5% improvement
- Source: http://www.info.uni-karlsruhe.de/lehre/2007WS/uebau1/folien/10-SSA_v2.pdf

Levels of optimizations

- **Local**
 - > within a single basic block, isolated from the others
- **Global (intraprocedural)**
 - > on a series of basic blocks, withing a control-flow graph
- **Interprocedural**
 - > analyses all of a program's code
 - > takes into account the context of the function calls
 - > rarely supported by compilers

Optimization using SSA

- Many optimizations are simpler in SSA form
- Two main transformations: normalization and optimization
- Normalization: making different expressions comparable with each other
 - > makes optimization easier
 - > uses algebraic identities: commutativity, associativity, distributivity
 - > can be limited by exceptions and prescribed evaluation order (e.g., Java)
- Optimization: making program execution more efficient

Dataflow analysis using SSA

- Some optimizations may change the execution order of statements
- Dataflow analysis: finding data dependencies
 - > definition-use of variables, dependencies of writes and reads
 - > important in the code generation phase for the correct ordering of operations
- Dataflow analysis can also be performed without SSA, however, usually it is easier with SSA
- Useful also for semantic analysis
 - > recognizing uninitialized variables
 - > reporting unused variables
 - > finding live (potentially used later) variables
 - > recognizing that a function does not return on all branches
 - > etc.

This lecture: Transformation, Optimization

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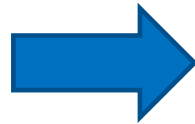
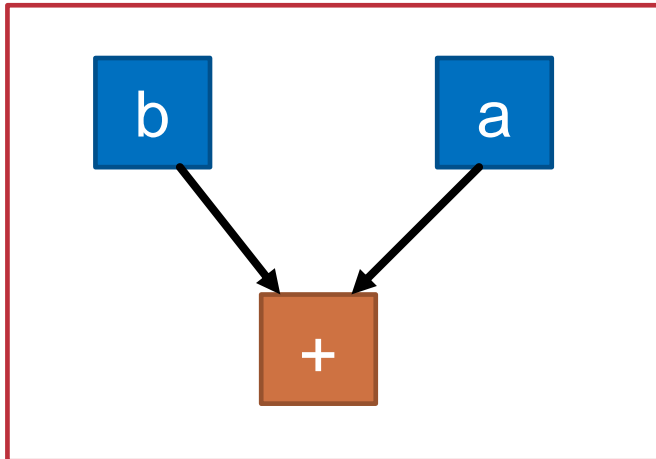
IV. Optimization

V. Optimization techniques

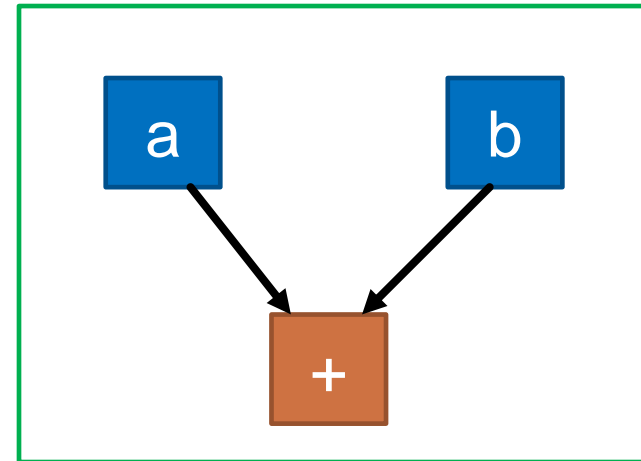


Normalization: using commutativity

t1: b+a



t1: a+b

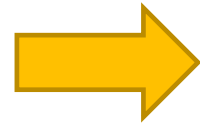


Common subexpressions can be recognized more easily

Optimization: elimination of common subexpressions

$x = b+a;$
 $y = (a+b)*2;$

SSA



$x1: b+a$
 $t2: a+b$
 $y1: t2*2$

Norm.

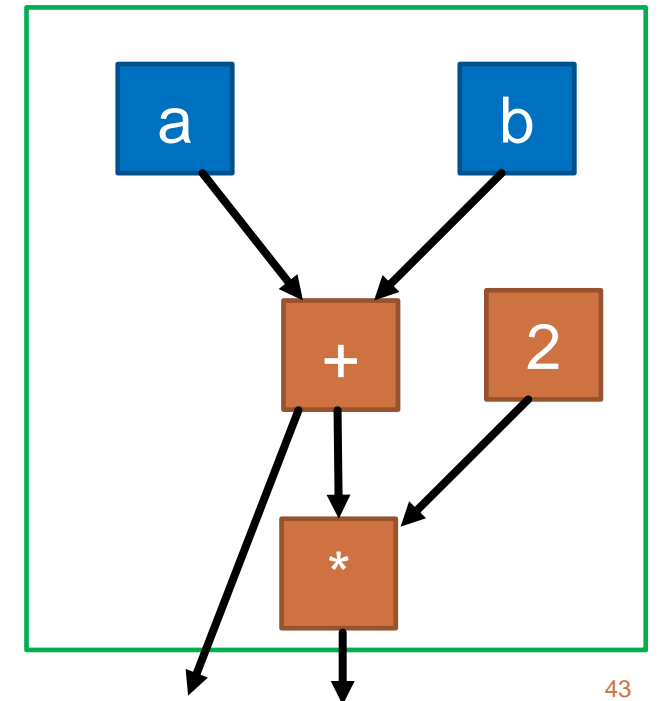
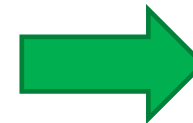
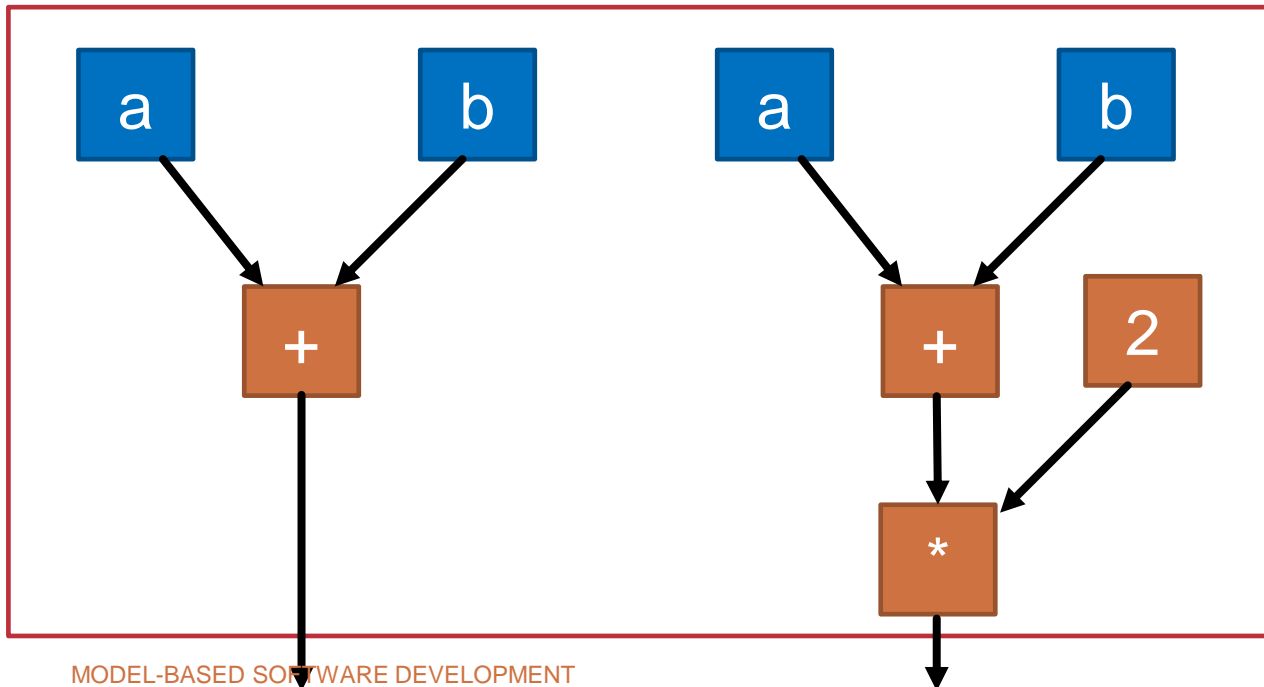


$x1: a+b$
 $t2: a+b$
 $y1: t2*2$

Opt.

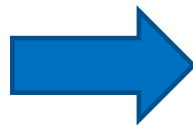
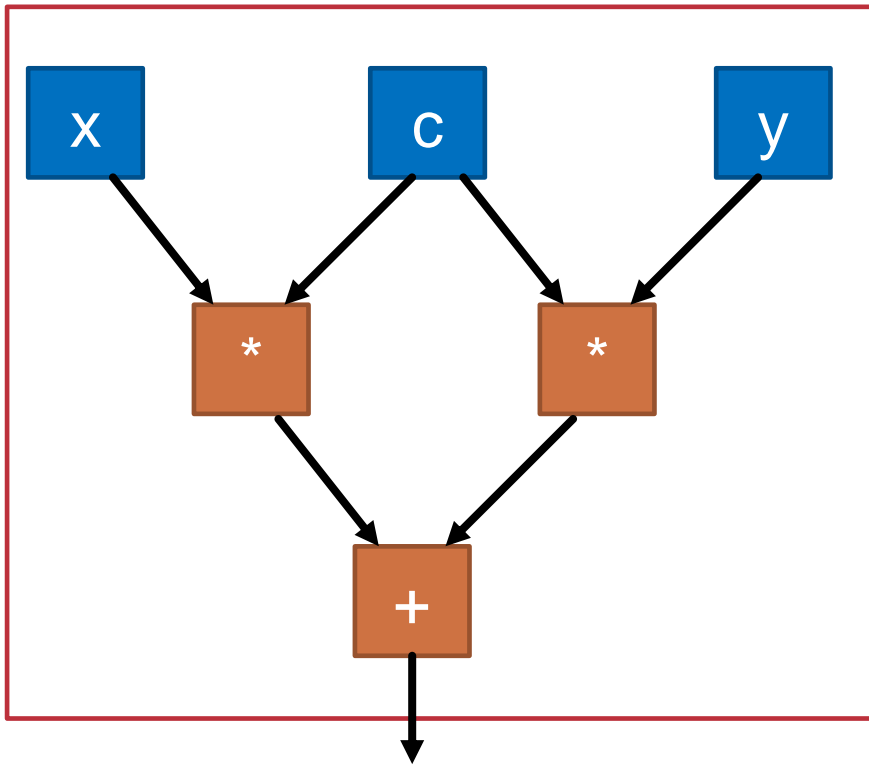


$x1: a+b$
 $y1: x1*2$

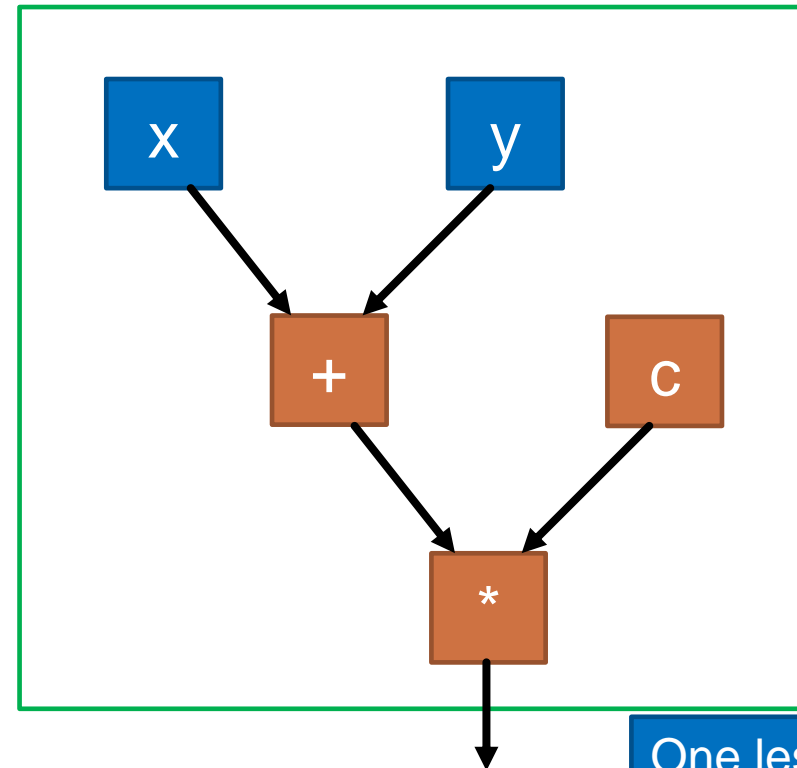


Normalization: using distributivity

t1: $x * c$
t2: $y * c$
t3: $t1 + t2$



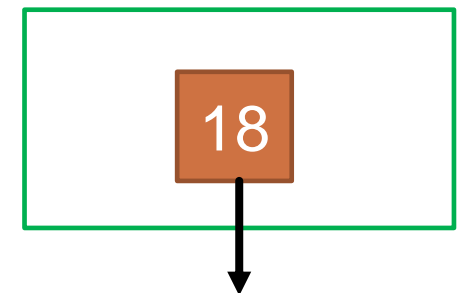
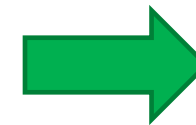
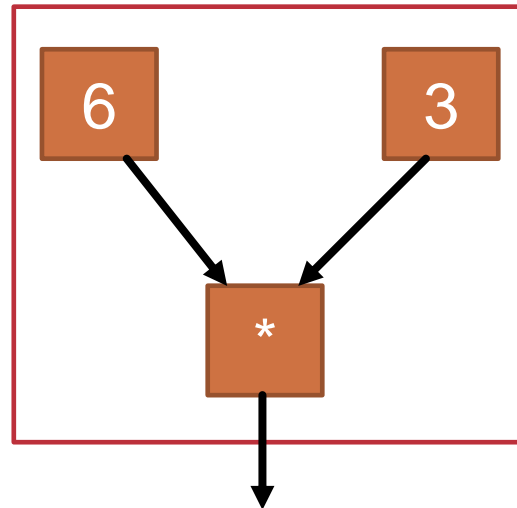
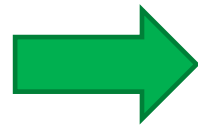
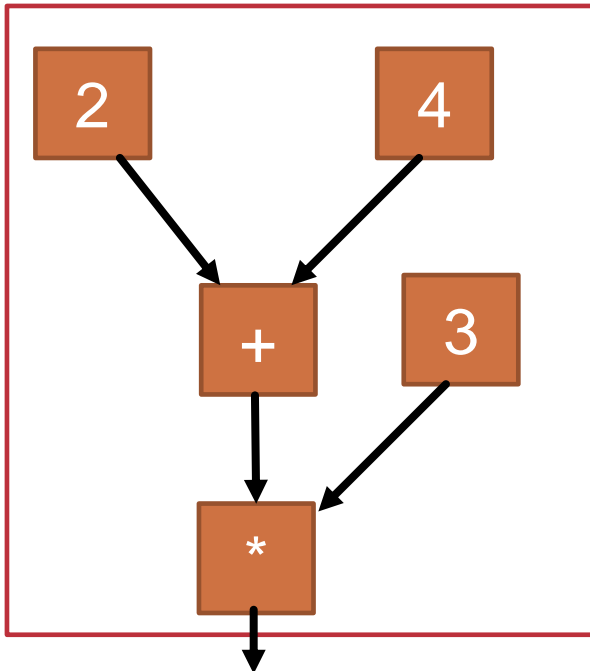
t1: $x + y$
t2: $t1 * c$



One less multiplication!

Optimization: evaluation of constant expressions

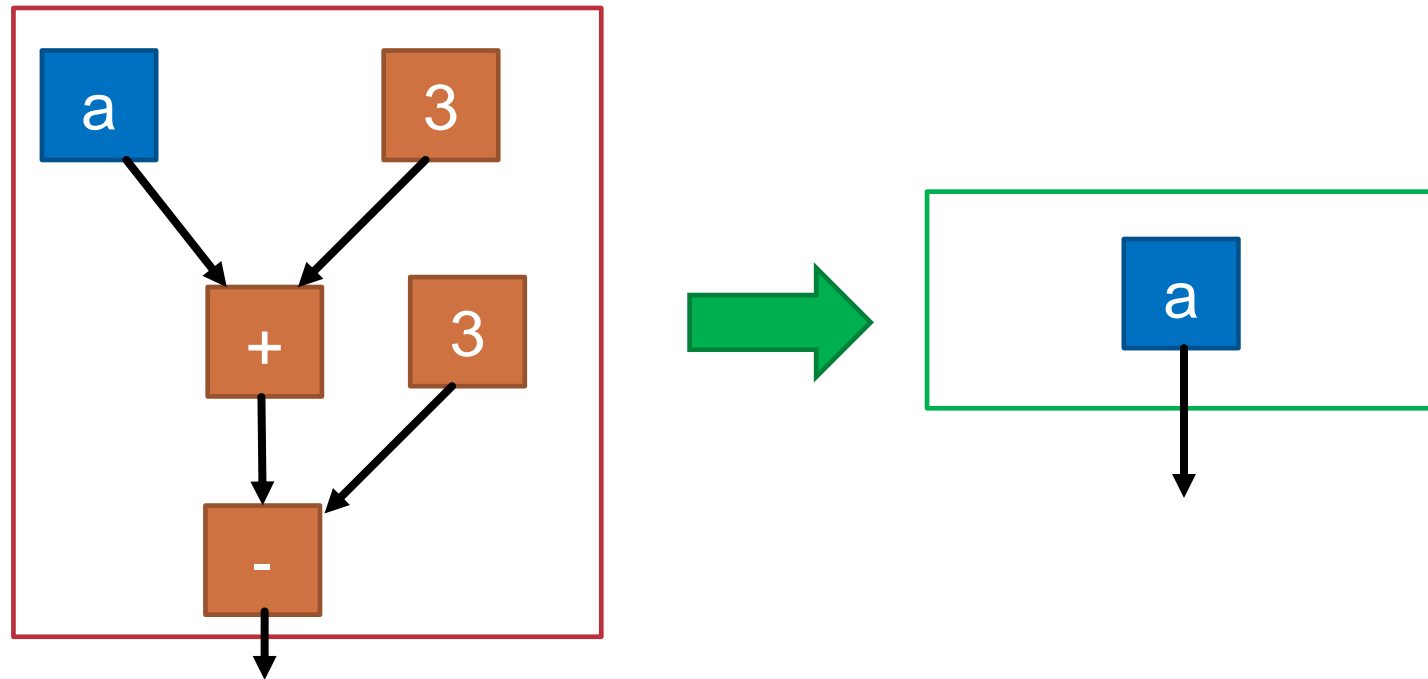
$x = 2+4;$
 $y = x*3;$ $\xrightarrow{\text{SSA}}$ $x1: 2+4$
 $y1: x1*3$ $\xrightarrow{\text{Opt.}}$ $x1: 6$
 $y1: x1*3$ $\xrightarrow{\text{Opt.}}$ $y1: 18$



Usually occurs during pointer arithmetic.

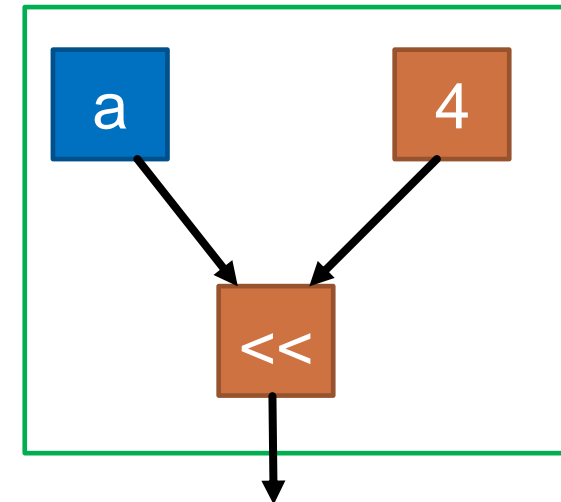
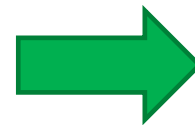
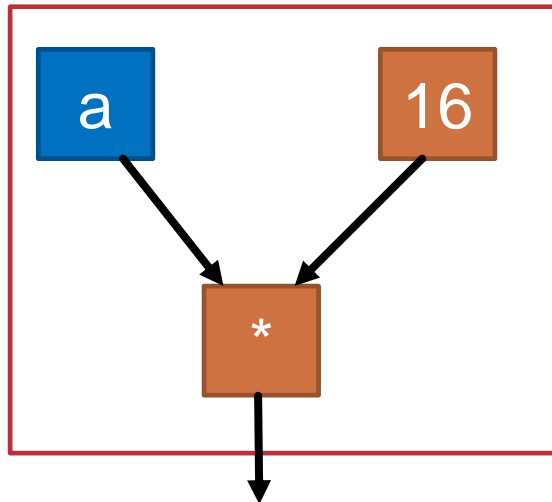
Optimization: removing inverse operator

$x = a+3;$
 $y = x-3;$ $\xrightarrow{\text{SSA}}$ $x1: a+3$
 $y1: x1-3$ $\xrightarrow{\text{Opt.}}$ $y1: a$



Optimization: operator simplification

`x = a*16;` $\xrightarrow{\text{SSA}}$ `x1: a*16` $\xrightarrow{\text{Opt.}}$ `x1: a << 4`

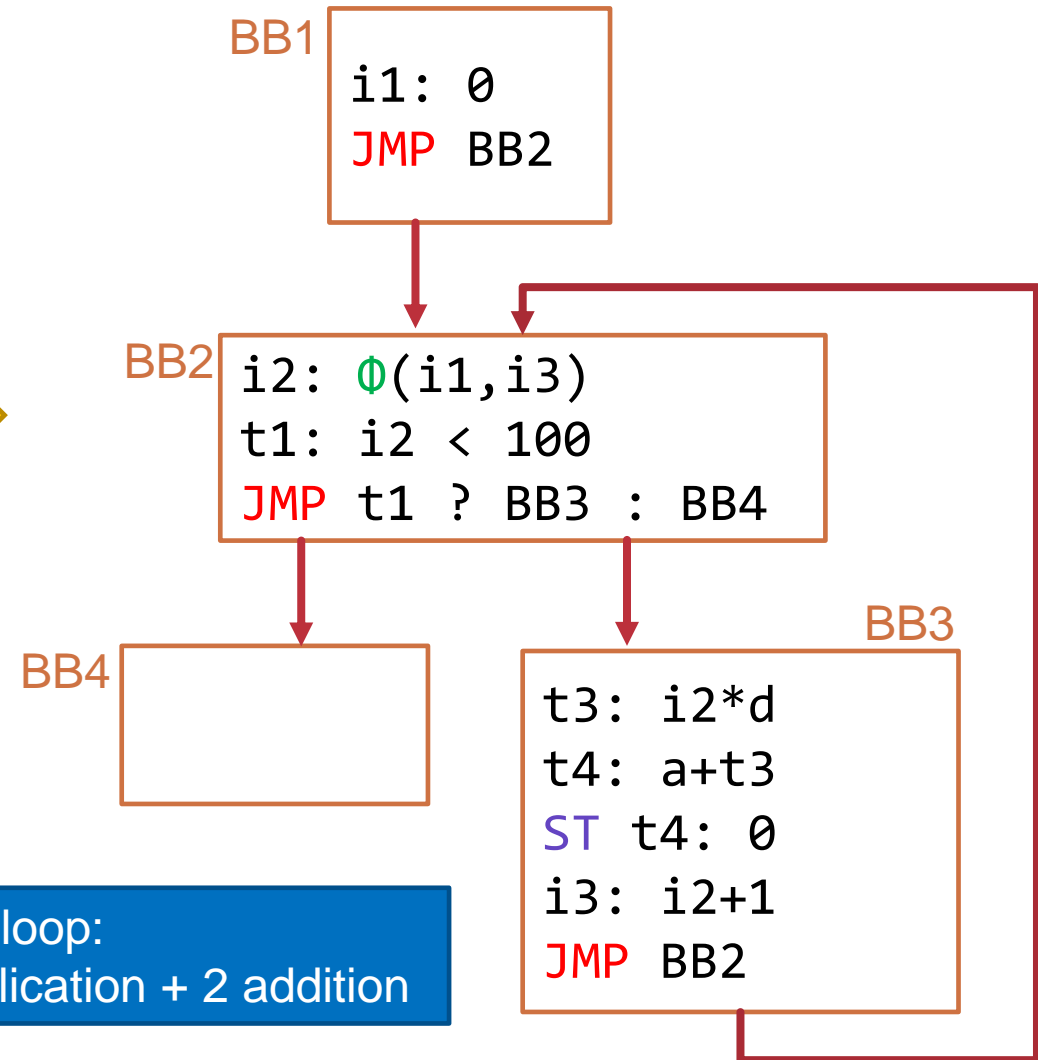


shift operator instead of multiplication with a power of 2

Optimization: simplifying loops (1/3)

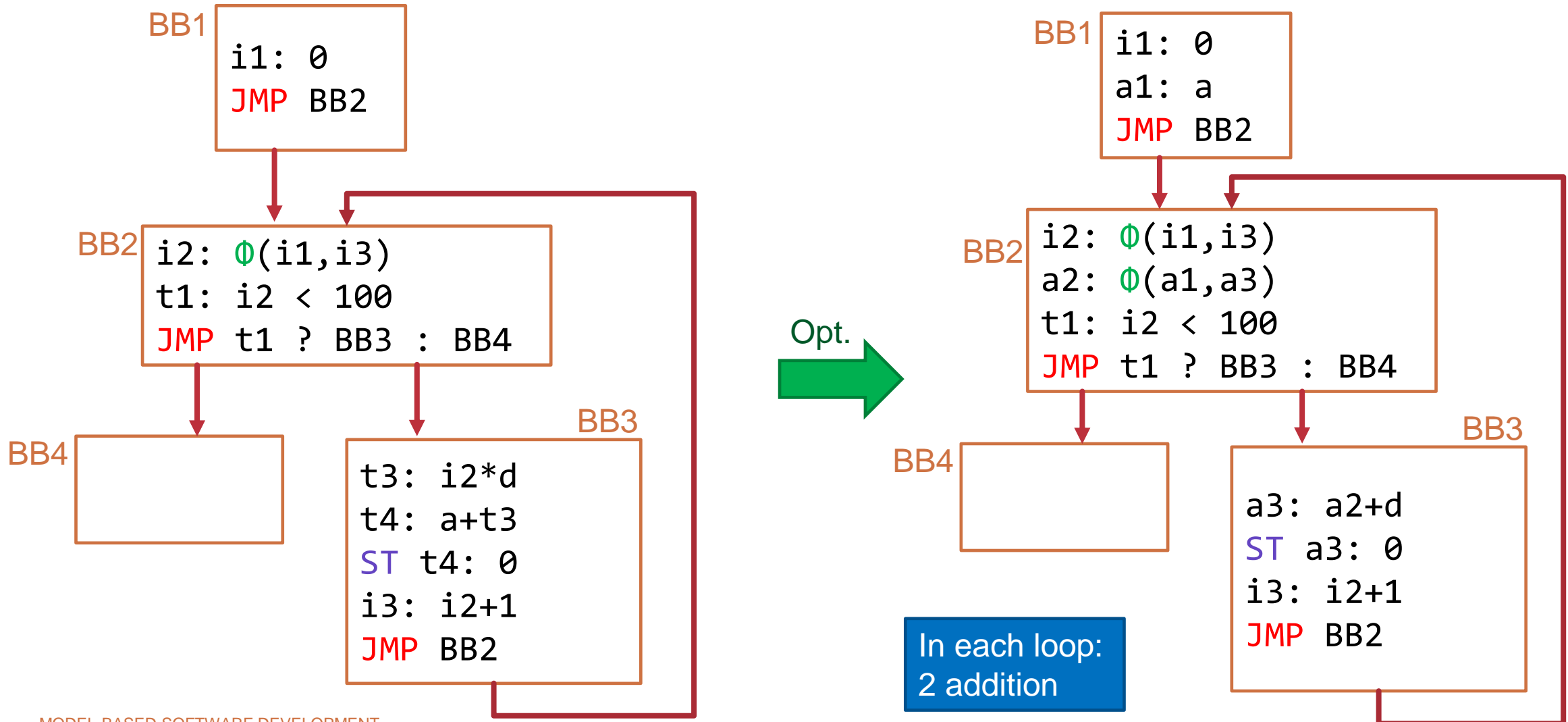
```
for (int i = 0; i < 100; ++i)
{
    a[i] = 0;
}
```

SSA

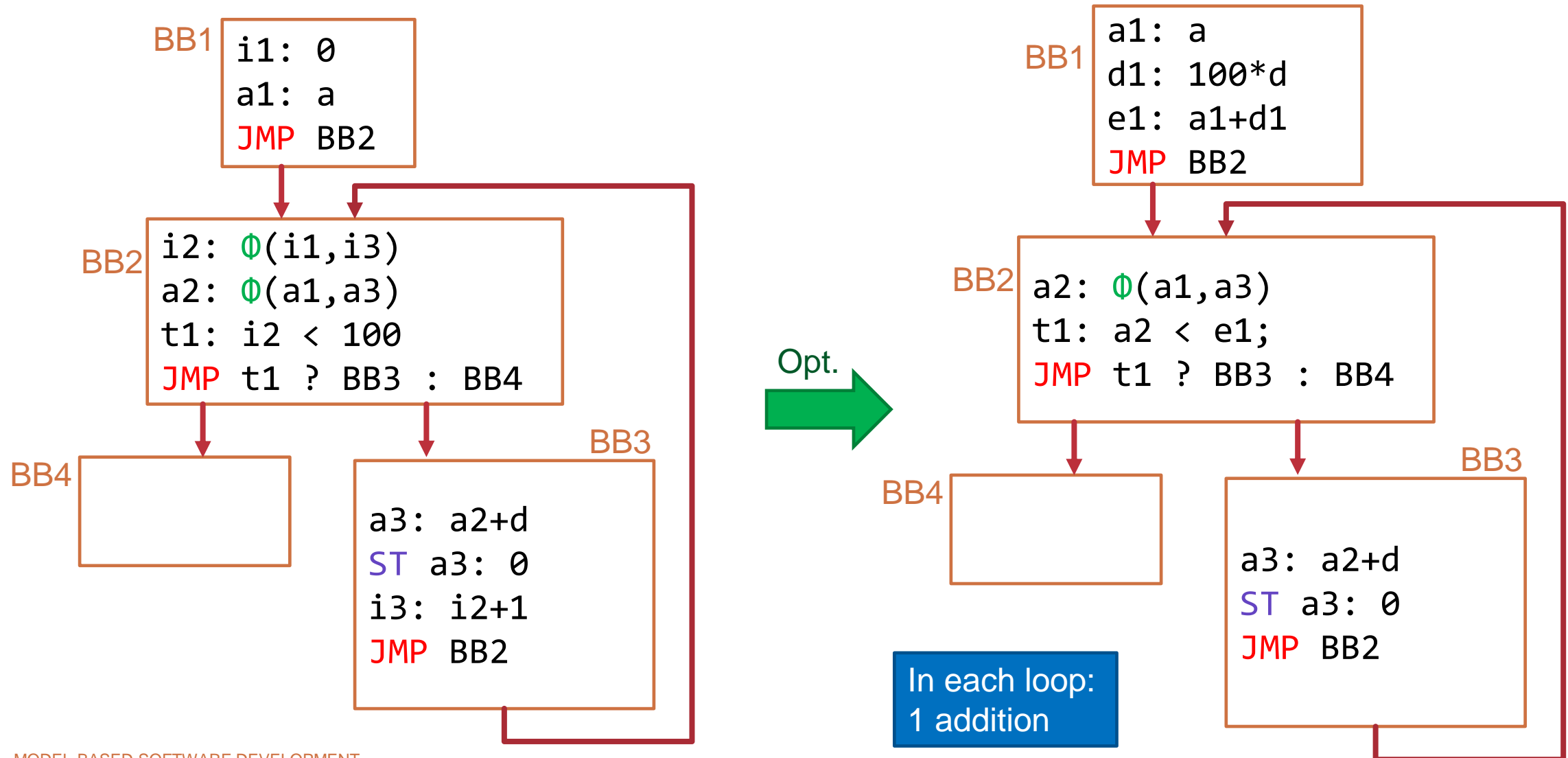


In each loop:
1 multiplication + 2 addition

Optimization: simplifying loops (2/3)



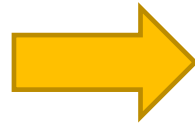
Optimization: simplifying loops (3/3)



Optimization: store-load

`a[1] = x;`
`y = a[1];`

SSA

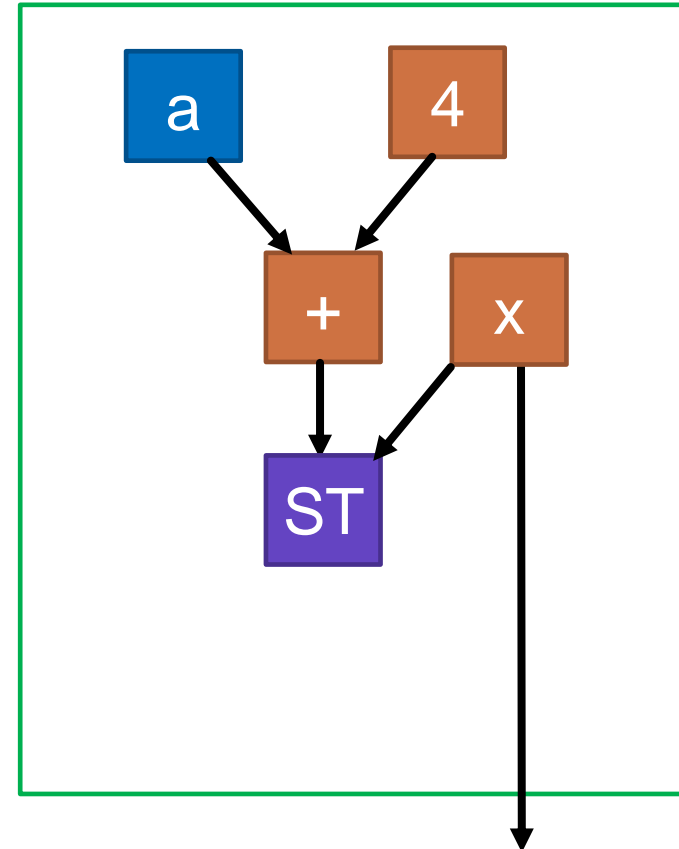
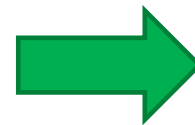
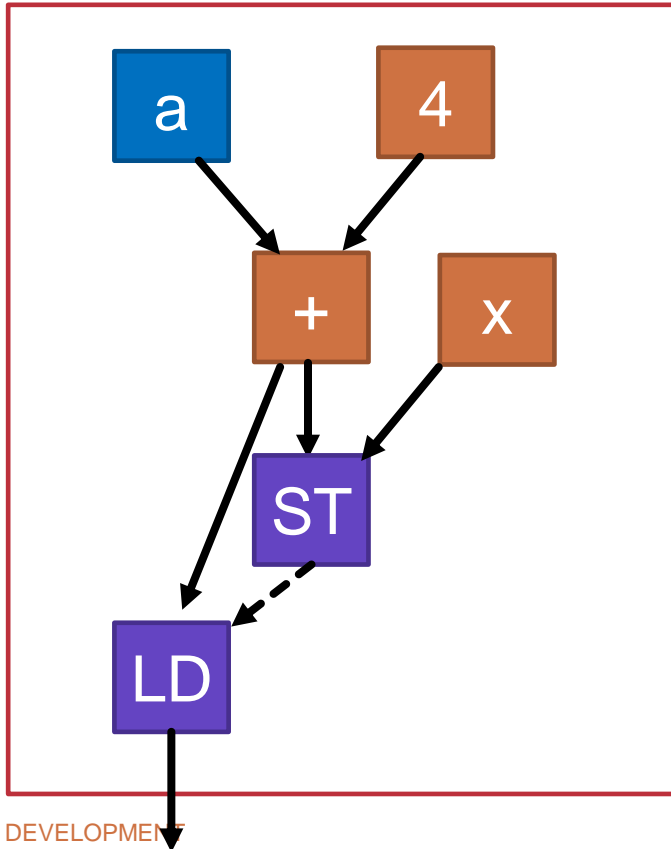


`t1: a+4`
`ST t1: x`
`y1: LD t1`

Opt.



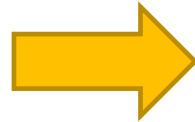
`t1: a+4`
`ST t1: x`
`y1: x`



Optimization: load-load

```
x = a[1];  
y = a[1];
```

SSA

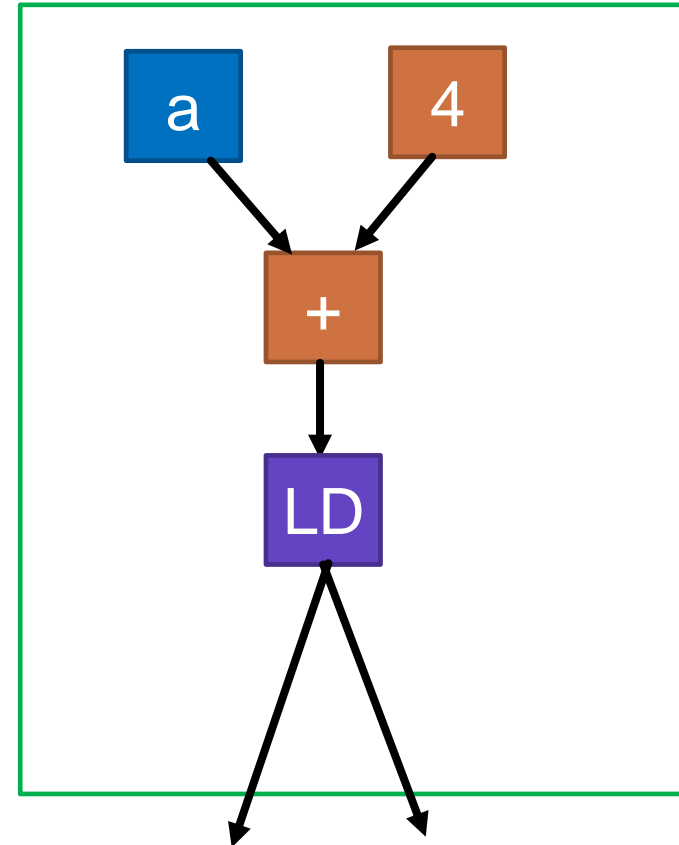
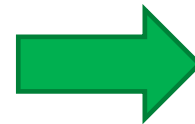
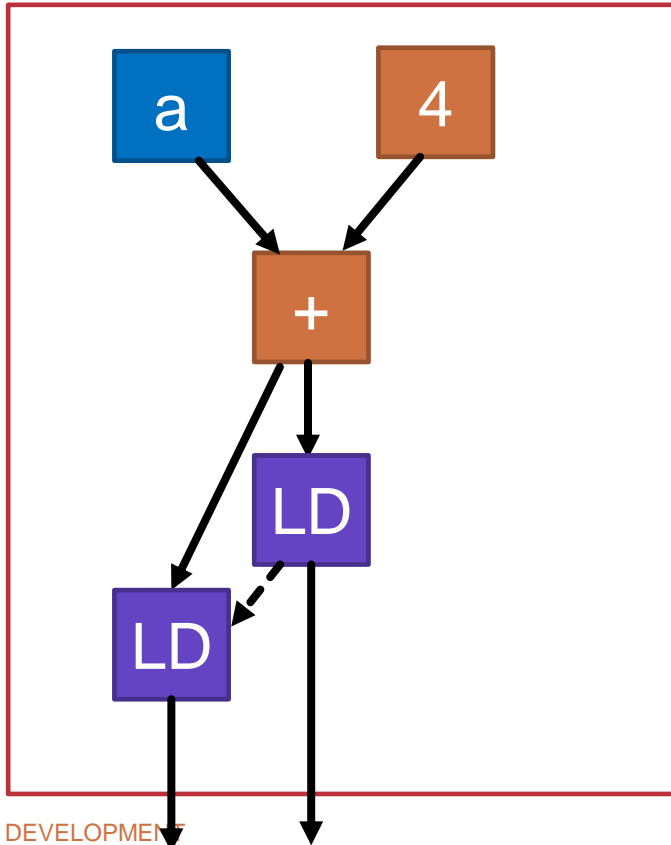


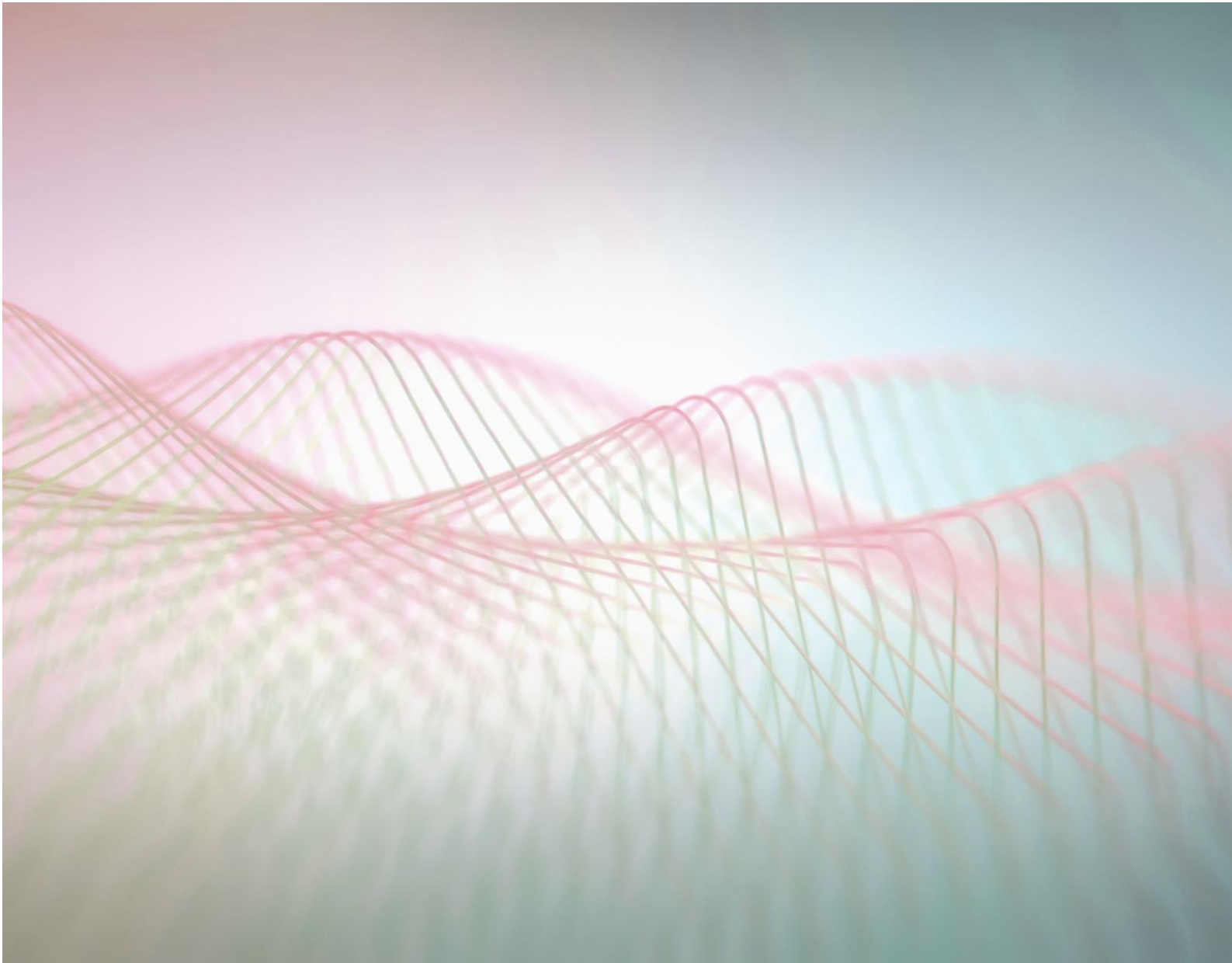
```
t1: a+4  
x1: LD t1  
y1: LD t1
```

Opt.



```
t1: a+4  
x1: LD t1  
y1: x1
```





Practice 3

Coming up next...

- Topic: IDE support for textual DSLs
- Eclipse environment – Java language
- Xtext – describing and processing DSLs, IDE support
- Xcore – meta-modeling (AST description at the same time)
- Xtend – template-based code generation
- IDE functions:
 - syntax highlighting, validation, error markers, content assist, hyperlinking, outline, automatic code formatting, automatic build / code generation



Thank you!