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Compilation Principle
编 译 原 理

第22讲：代码优化(2)

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Review Questions

- Q1: Code optimizations are to generate better code, list some 'better' metrics.

  Execution time, memory usage, energy, binary size…

- Q2: what is a Basic Block?

  A straight-line sequence of code with only one entry point and only one exit.

- Q3: how to partition code into BBs?

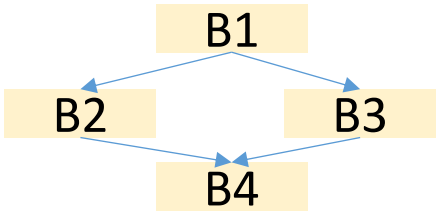
  Identify leader insts; a BB consists of a leader inst and subsequent insts before next leader.

- Q4: What is a control-flow graph?

  A directed graph where nodes are BBs, edges show flow of execution between BBs.

- Q5: What is the CFG of the listed code?

```
     w = 0          B1
     y = 0
     x = x + y
     if x > z: goto L1
     y = z          B2
     z ++
     goto L2
L1:  y = x          B3
     x ++
L2:  w = x + z      B4
```



Local and Global Optimizations

- Local optimizations[局部优化]
  - Optimizations performed exclusively within a basic block
  - Typically the easiest, never consider any control flow info
    - All instructions in scope executed exactly once
  - Examples:
    - constant folding[常量折叠]
    - common subexpression elimination[删除公共子表达式]

- Global optimizations[全局优化]
  - Optimizations performed across basic blocks
    - Scope can contain if / while / for statements
    - Some insts may not execute, or even execute multiple times
  - Note: global here doesn't mean across the entire program
    - We usually optimize one function at a time

Local Optimization: Examples

- Common subexpression elimination[删除公共子表达式]
  - Two operations are common if they produce the same result
    - It is likely more efficient to compute the result once and reference it the second time rather than re-evaluate it[避免重复计算]
- Dead code elimination[删除无用代码]
  - If an instruction's result is never used, the instruction is considered "dead" and can be removed from the instruction stream[结果从不使用]

```
y = x + z;
y = x * x  + (x/3)
z = x * x + y;
```

```
y = x + z;
t1 = x * x
t2 = x / 3
y = t1  + t2
t3 = x * x
z = t3 + y;
```

```
y = x + z;
t1 = x * x
t2 = x / 3
y = t1  + t2
t3 = x * x
z = t1 + y;
```

DAG of Basic Blocks

- Many important techniques for local optimization begin by transforming a BB into a DAG (directed acyclic graph)[无环有向图]

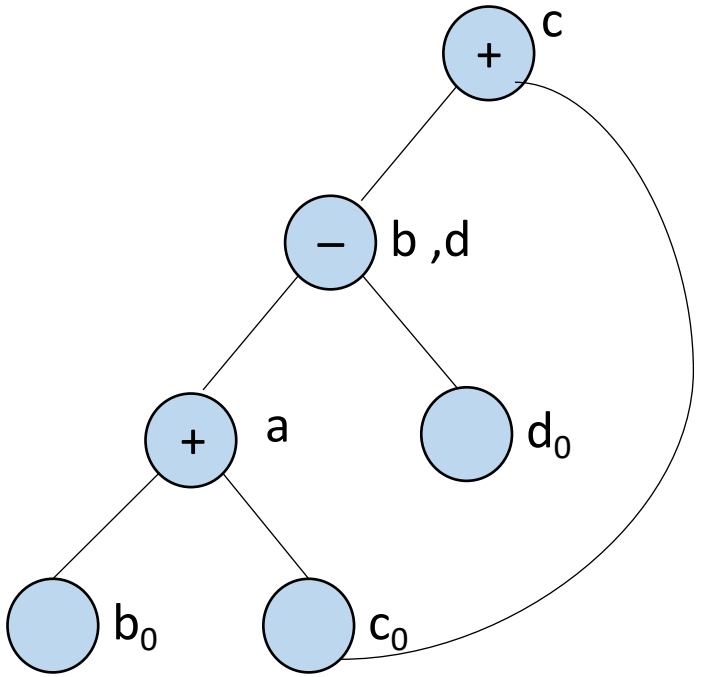
- To construct a DAG for a BB as follows
  - Create a node for each of the initial values of the variables appearing in the BB[为变量初始值创建节点，叶子]
  - Create a node *N* associated with each statement *s* within the block[为声明语句创建节点，中间]
    - The children of *N* are those nodes corresponding to statements that are the last definitions, prior to *s*, of the operands used by *s*
    - Label *N* by the operator applied at *s*[用运算符标注节点]
  - Certain nodes are designated output nodes[某些为输出节点]
    - These are the nodes whose variables are *live on exit* from the block (i.e., their values may be used later, in another block of the flow graph)

Example: DAG

- (3) c = b + c
  - *b* refers to the node labelled '-'
    - Most recent definition of *b*

(1) a = b + c
(2) b = a – d
(3) c = b + c
(4) d = a – d

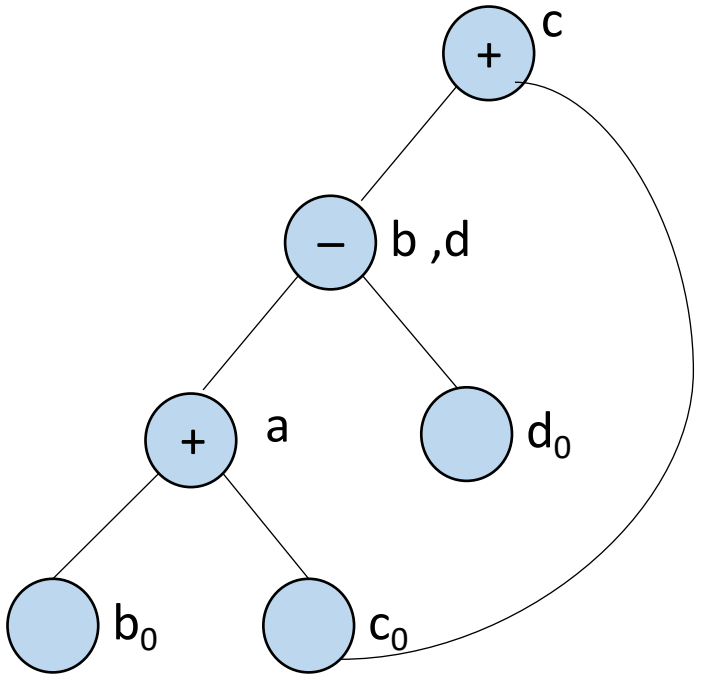
- (4) d = a – d
  - Operator and children are the same as the 2nd statement
    - Reuse the node



Local Opt.: Elimination

- If *b* is not live on exit from the block
  - No need to keep *b = a – d*
- If both *b* and *d* are live
  - Remove either (2) or (4) : **common subexpr elimination**
  - Add a 4th statement to copy one to the other
- If only *a* is live on exit
  - Then remove nodes from the DAG correspond to dead code
    - c -> b,d -> d_0
  - This is actually **dead code elimination**

(1) a = b + c
(2) b = a – d
(3) c = b + c
(4) d = a – d

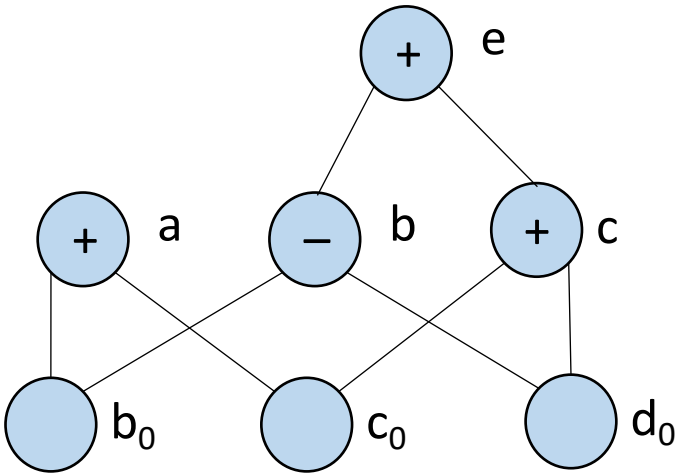


Local Opt.: Elimination (cont.)

- When finding common subexprs, we really are finding exprs that are guaranteed to compute the same value, no matter how that value is computed[过于严苛]
  - Thus miss the fact that (1) and (4) are the same
    - $b + c = (b - d) + (c + d) = b_0 + c_0$

(1) a = b + c
(2) b = b – d
(3) c = c + d
(4) e = b + c

- **Solution**: algebraic identities[代数恒等式]



Local Opt.: Algebraic Identities[代数恒等式]

- Eliminate computations by applying mathematical rules[使用数学规则]
  - Identities: a * 1 ≡ a, a * 0 ≡ 0, b & true ≡ b
  - Reassociation and commutativity[重组合、交换]
    - (a + b) + c ≡ a + (b + c) , a + b ≡ b + a
- **Strength Reduction**[强度削减]
  - Replacing expensive operations (*multiplication*, *division*) by less expensive operations (*add*, *sub*, *shift*)
  - Some ops can be replaced with cheaper ops
  - Examples
    - x=y/8 --> x=y»3
    - y=y*8 --> x=y«3
    - x^2 --> x * x
    - 2 * x --> x + x

Local Opt.: Constant Folding[常量折叠]

- **Constant Folding**
  - Computing operations on constants at compile time
  - Example:

```
#define LEN 100
x = 2 * LEN;
if (LEN < 0) print(”error”);
```

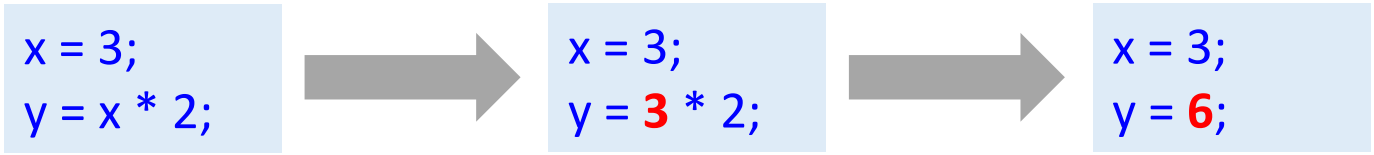
  - After constant folding

```
x = 200;
if (false) print(”error”);
```

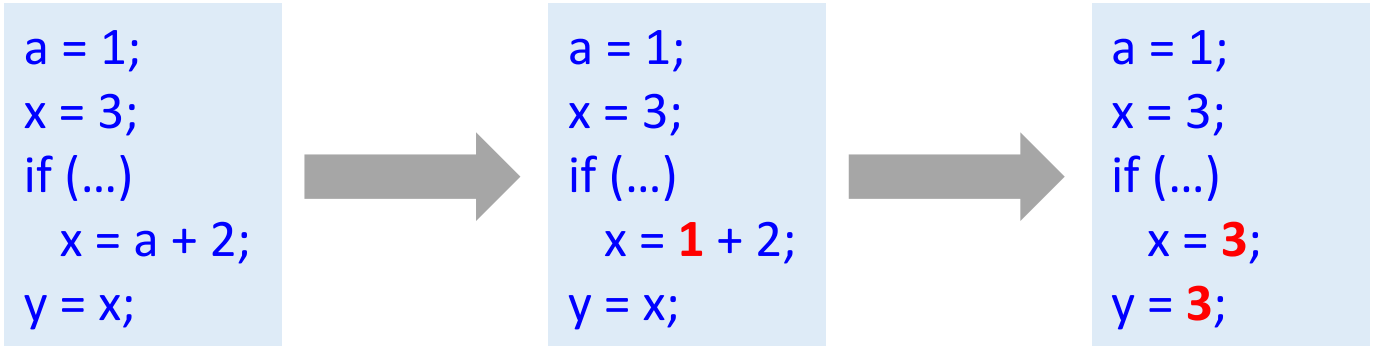
  - Dead code elimination can further remove the above *if* statement
  - Inherently local since scope limited to statement

Local Opt.: Constant Propagation[常量传播]

- **Constant Propagation**
  - Substituting values of known constants at compile time
  - Local Constant Propagation (LCP)



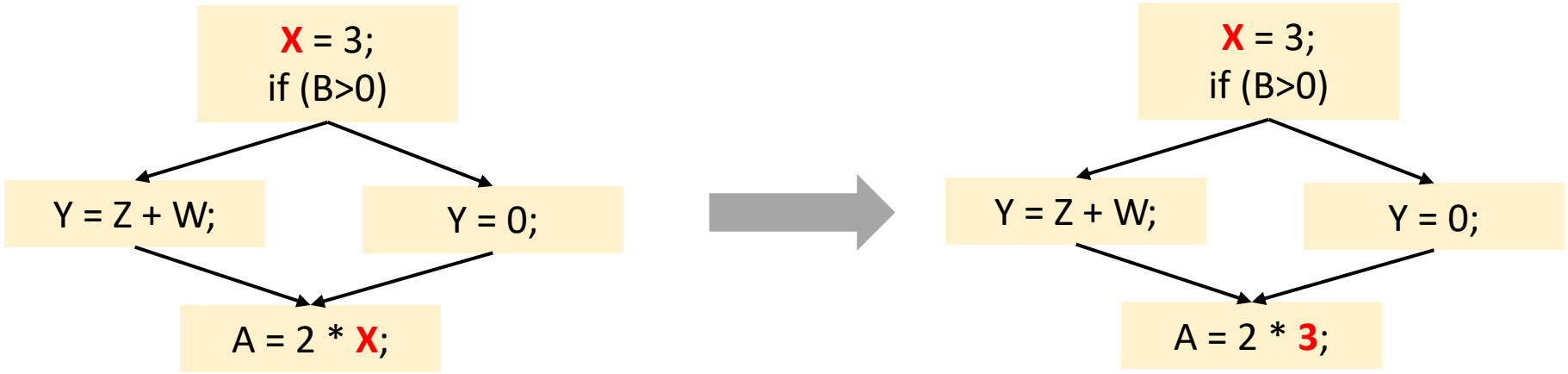
- Some optimizations have both local and global versions
  - Global Constant Propagation (GCP)

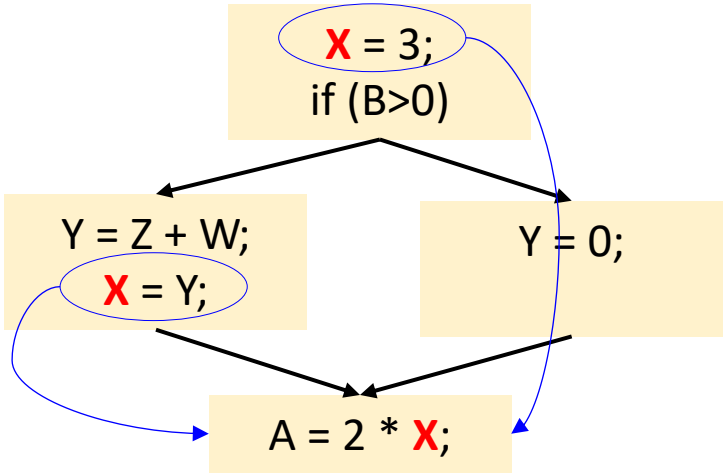


  - GCP more powerful than LCP but also more complicated
    - Must determine *x* is constant across all paths reaching *x*

Global Optimizations

- Extend optimizations to flow of control, i.e. CFG
  - Along **all paths**, the last assignment to X is "X=C"
  - Optimization must be stopped if incorrect in even one path





Global Opt.: Conservative[需保守]

- Compiler must prove some property X at a particular point
  - Need to prove at that point property X holds along all paths
  - Need to be **conservative** to ensure correctness
    - An optimization is enabled only when X is definitely true
    - If not sure if it is true or not, it is safe to say **don't know**
    - If analysis result is **don't know**, no optimization done
    - May lose opt. opportunities but guarantees correctness
- Property X often involves data flow of program
  - E.g. Global Constant Propagation (GCP):

```
X = 7;
...
Y = X + 3; // Does value of 7 flow into this use of X?
```

  - Needs knowledge of **data flow**, as well as control flow
    - Whether data flow is interrupted between points A and B

Global Opt.: Data Flow[数据流]

- Most optimizations rely on a property at given point
  - For Global Constant Propagation (GCP):

    A = B + C; // Property: {A=?, B=10, C=?}
  - After optimization:

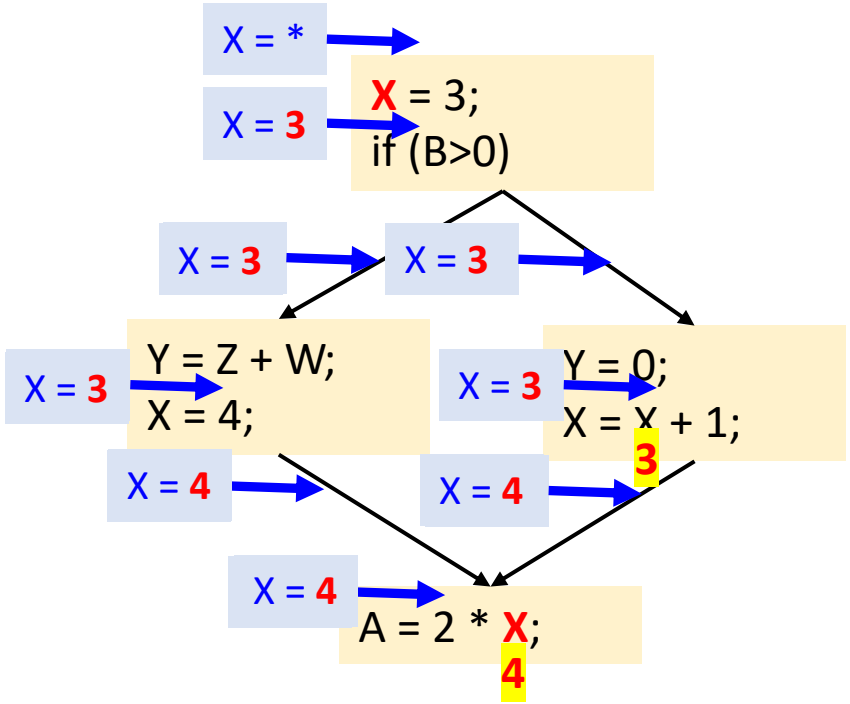
    A = 10 + C;
- For this discussion, let's call these properties ***values***
- **Dataflow analysis**: compiler analysis that calculates values for each point in a program
  - Values get propagated from one statement to the next
  - Statements can modify values (for GCP, assigning to vars)
  - Requires CFG since values flow through control flow edges
- **Dataflow analysis framework**: a framework for dataflow analysis that guarantees correctness for **all paths**
  - Does *not* traverse all possible paths (could be infinite)
  - To be feasible, makes **conservative** approximations

Global Constant Propagation (GCP)

- Let's apply dataflow analysis to compute values for GCP
  - Emulates what human does when tracing through code
- Let's use following notation to express the state of a var:
  - x=*: not assigned (default)
  - x=1, x=2, ...: assigned to a constant value
  - x=#: assigned to multiple values
- All values start as x=* and are iteratively refined
  - Until they stabilize and reach a fixed point
- Once fixed point is reached, can replace with constants:
  - x=*: replace with any constant (typically 0)
  - x=1, x=2, ...: replace with given constant value
  - x=#: cannot do anything

Example

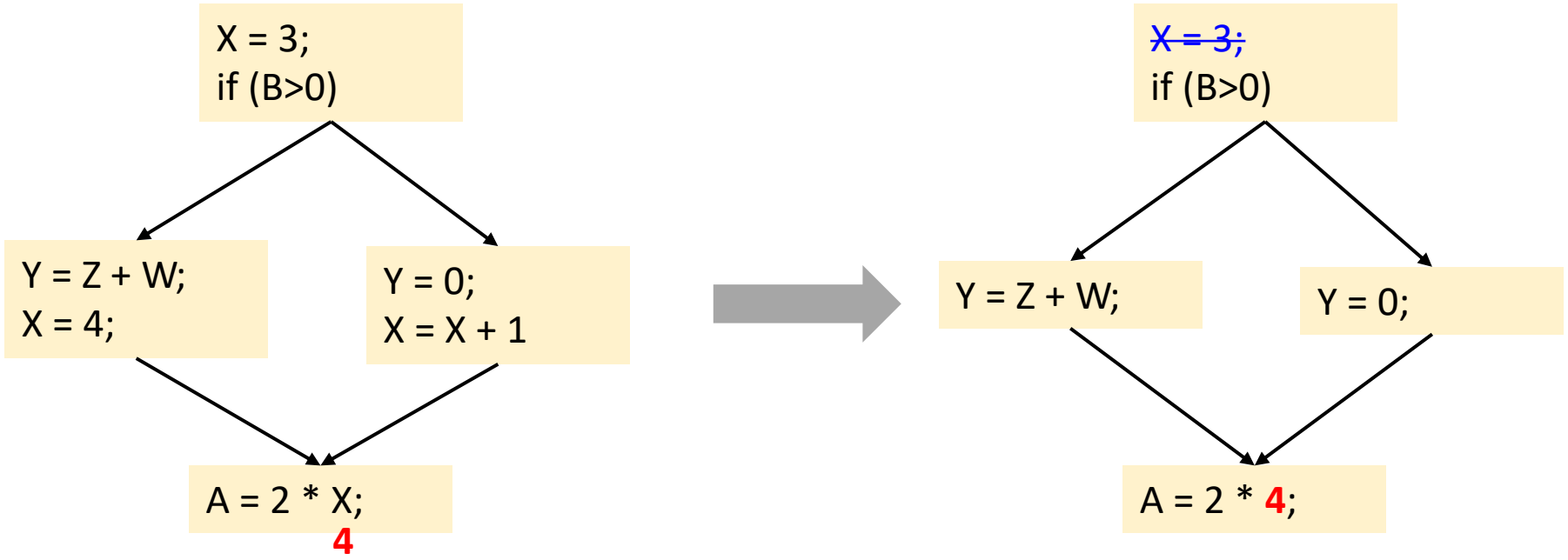
- In this example, constants can be propagated to **X+1**, **2*X**
- Statements visited in reverse postorder (predecessor first)



x=*: not assigned (default)
x=1, x=2, ...: assigned to a constant value
x=#: assigned to multiple values

Example (cont.)

- Once constants have been globally propagated, we would like to eliminate the dead code



Machine Optimizations[机器相关优化]

- After performing IR optimizations
  - We need to further convert the optimized IR into the target language (e.g. assembly, machine code)
- Specific machines features are taken into account to produce code optimized for the particular architecture[考虑特定的架构特性]
  - E.g., specialized instructions, hardware pipeline abilities, register details
- Typical machine optimizations[典型的优化方案]
  - **Instruction selection and scheduling**: select insts to implement the operators in IR
  - **Register allocation**: map values to registers and manage
  - **Peephole optimization**: locally improve the target code

Instruction Selection[指令选取]

- To find an efficient mapping from the IR of a program to a target-specific assembly listing[IR到汇编的映射]
- Instruction selection is particularly important when targeting architectures with CISC (e.g., x86)
  - In these architectures there are typically several possible implementations of the same IR operation, each with different properties
  - e.g., on x86 an addition of one can be implemented by an *inc*, *add*, or *lea* instruction

x = y + z

```
MOV y,R0
ADD z,R0
MOV R0,x
```

a = a + 1

```
MOV a,R0
ADD #1,R0
MOV R0,a
```

```
MOV a,R0
INC R0
MOV R0,a
```

Instruction Scheduling[指令调度]

- Some facts
  - Instructions take clock cycles to execute (latency)
  - Modern machines issue several operations per cycle (Out-of-Order execution)
  - Cannot use results until ready, can do something else
  - Execution time is order-dependent
- Goal: reorder the operations to minimize execution time
  - Minimize wasted cycles
  - Avoid spilling registers
  - Improve locality

```
A = x * y;
B = A + 1;
C = y;
```

```
A = x * y;
C = y;
B = A + 1;
```

(Now C=y; can execute while waiting for A=x*y;)

Register Allocation[寄存器分配]

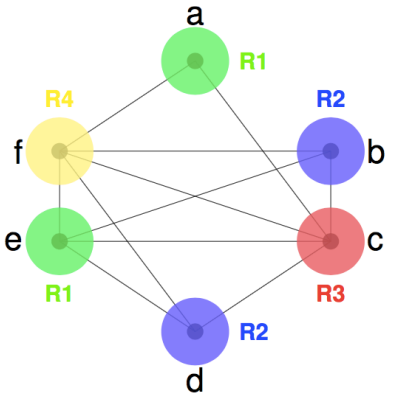
- In TAC, there are an unlimited number of variables
  - On a physical machine there are a small number of registers
- **Register allocation** is the process of assigning variables to registers and managing data transfer in and out of registers
  - How to assign variables to finitely many registers?
  - What to do when it can't be done?
  - How to do so efficiently?
- Using registers intelligently is a critical step in any compiler
  - Accesses to memory are costly, even with caches
  - A good register allocator can generate code orders of magnitude better than a bad register allocator

Register Allocation (cont.)

- Goals of register allocation
  - Keep frequently accessed variables in registers
  - Keep variables in registers only as long as they are live
- Local register allocation[局部]
  - Allocate registers basic block by basic block
  - Makes decisions on a per-block basis (hence ‘local’)
- Global register allocation[全局]
  - Makes global decisions about register allocation such that
    - Var to reg mappings remain consistent across blocks
    - Structure of CFG is taken into account on decisions
- Three well-known register allocation algorithms
  - Graph coloring allocator[图着色]
  - Linear scan allocator[线性扫描]
  - LP (Integer Linear Programming) allocator[整数线性规划]

Graph Coloring[图着色]

- Register interference graph (RIG)[相交图]
  - Each node represents a variable
  - An edge between two nodes V_1 and V_2 represents an interference in live ranges[活跃期/生存期]
- Based on RIG,
  - Two variables can be allocated in the same register if there is no edge between them[若无边相连，可使用同一寄存器]
  - Otherwise, they cannot be allocated in the same register
- Problem of register allocation maps to graph coloring
  - Once solved, *k* colors can be mapped back to *k* registers
  - If the graph is *k*-colorable, it's *k*-register-allocatable



Register Spilling[寄存器溢出]

- Determining whether a graph is *k*-colorable is NP-complete
  - Therefore, problem of *k*-register allocation is NP-complete
  - In practice: use heuristic polynomial algorithm that gives close to optimal allocations most of the time
  - Chaitin's graph coloring is a popular heuristic algorithm
    - E.g. most backends of GCC use Chaitin's algorithm
- What if *k*-register allocation does not exist?
  - Spill a variable to memory to reduce RIG and try again
  - Spilled var stays in memory and is not allocated a reg
- Spilling is slow
  - Placed into memory, loaded into register when needed, and written back to memory when no longer used

Peephole Optimization[窥孔优化]

- Optimization ways
  - Usual: produce good code through careful inst selection and register allocation
  - Alternative: generate naïve target code and then improve
- A simple but effective technique for locally improving the target code[很局部的优化，但可能带来性能的极大提升]
  - Done by examining a sliding window of target instructions (called **peephole**) and replacing instruction sequences within the peephole by a shorter or faster sequence, whenever psbl
  - Can also be applied directly after IR generation to improve IR
- Example transformations
  - Redundant-instruction elimination
  - Flow-of-control optimizations
  - Algebraic simplifications
  - Use of machine idioms

```
    if a < b goto L1
    …
L1: goto L2
```

Jump to jumps

```
    if a < b goto L2
    …
L1: goto L2
```

Summary[总结]

- Code can be optimized at different levels with various techniques
  - IR: local, global, common subexpression elimination, constant folding and propagation, …
  - Target: instruction, register, peephole, …
- Interactions between the various optimization techniques
  - Some transformations may expose possibilities for others
  - One opt. may obscure or remove possibilities for others
- Affect of compiler opts are intertwined and hard to separate
  - Finding optimal opt combinations is in itself research
  - Compilers package opts that typically go together into levels (e.g -O1, -O2, -O3)


The END is Near

期末考试

- 编译原理
  - 课堂参与（10%） - 点名、提问、测试 [3次测试]
  - 课程作业 （20%）- 4次左右，理论 [2次作业]
  - 期中考查 （10%）- 课下习题 [1次练习]
  - 期末考试 （60%）- 闭卷

参考答案已上传

- 考试时间
  - 14:30-16:30
  - 7月8日(周四)
- 题目类型
  - 判断题
  - 简答题
  - 应用题
  - 综合应用题
- 主要内容
  - 词法分析
  - 语法分析
  - 语义分析
  - 代码生成及优化

Exam should NOT be the END …

Front-end (15x2学时)	Back-end (7x2学时)	Talk (2x2学时)	Intro+Review (2x2学时)

期末考试分值分布

科研/工作相关性