6.035 Project 4: Dataflow Optimization

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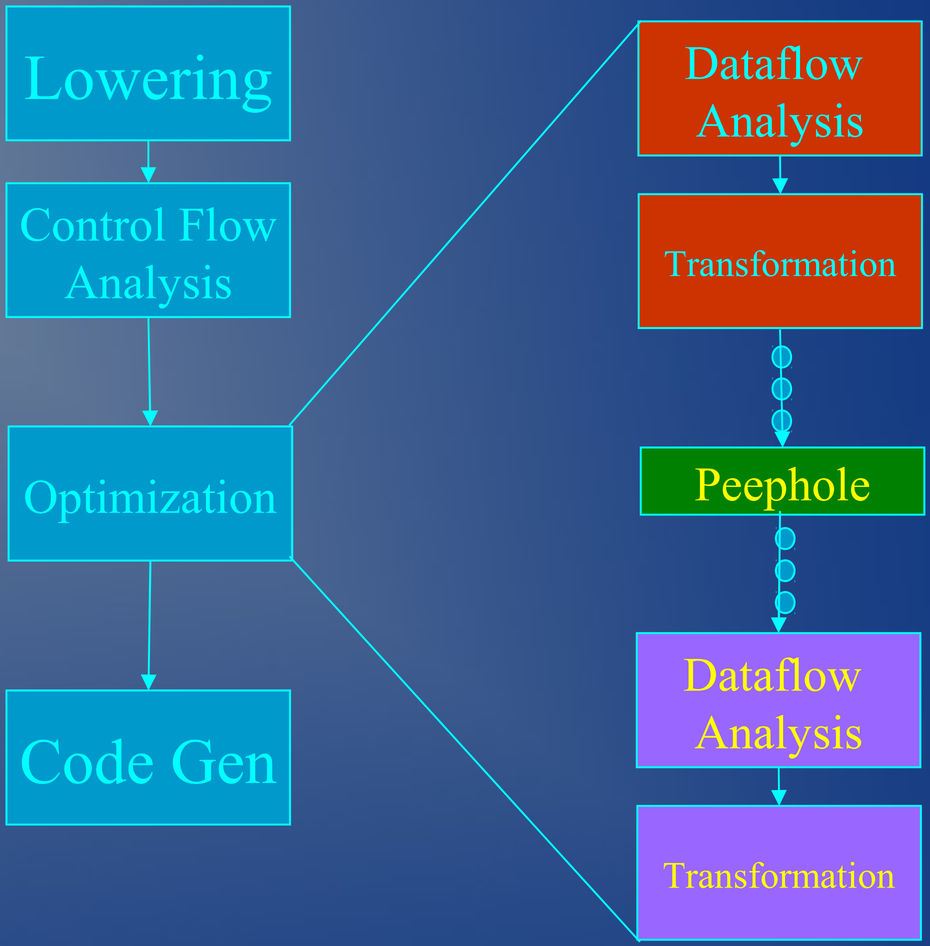
An “Optimizing” Compiler

- Somehow make the code better (on average):
  - Faster
  - Smaller memory footprint of code
  - Less memory used during run
- How to prove this:
  - Experimentation on benchmark suite!
- Must preserve the meaning of the original program!
  - Including errors!

An Optimizing Compiler



Low IR (or Mid IR)

- Do analysis on low-level IR (does this fit what you had for code gen?)
  - Simple computations: a = b + c
  - explicit array accesses
  - gotos
  - labels
  - moves
  - calls
- See Tiger chp. 17 or Whale chp. 4

Lowering Cont.

- Perform transformations on your IR:
  - Global CSE
  - Loop invariant code motion
  - Copy propagation
  - DCE
- Some optimizations may work better if you have info from high level IR
  - Parallelization
  - Maybe easier to do in High-level IR?

Control-Flow Analysis

- Convert the intermediate code into graph of *basic blocks*
- Basic block:
  - sequence of instructions with a single entry and a single exit
  - Control must enter at beginning and leave at end
- Simple to convert to a control flow graph
  - find heads of basic block:
    - after jump
    - target of jump

Peephole Optimizations

- Examine a short sequence of instructions
- Try to replace with a better sequence
- Examples:
  - Flow of controls
    - jumps to jumps
  - Algebraic Simplification
    - $x + 0 \rightarrow x$
  - Strength Reduction
    - $x * 3 \rightarrow x + x + x$
    - Look at AMD64 documentation

Inline Function Expansion (Procedure Integration)

- Replace a function call with the body of the function
- Usually done on high-level IR (AST)
- Careful:
  - Performance?
  - Recursion?!
  - Names…

Example

```
Program {
  int x;
  void foo() {
     x = 2;
  }

  void main() {
     {
          int x;
          foo();
     }
     print(x);
  }
```

Example

```
Program {
  int x;
  void foo() {
      x = 2;
  }

  void main() {
      {
            int x;
            x = 2;
      }
      print(x);
  }
```

“Global” Optimizations

- Global mean inter-basic block and intra-procedural
- You can inline functions
- Operate on control flow graph of basic blocks
  - You can use a CFG of MIR or LIR
- Usually:
  - Perform some dataflow analysis to find candidates
  - Validate the correct of candidates using other tests

Iterative Dataflow Analysis

- Use bit vectors to represent the information
  - instructions, expressions, variables, etc.
- Set of dataflow equations
- Iterate until a fixed point is reached
- For each basic block, b:
  - IN[b] – information that flows into block
  - OUT[b] – information that flows out of block
  - What happens inside the block

Example: Reaching Defs

- Concept of definition and use
  - a = x+y
  - is a definition of a
  - is a use of x and y
- Given a program point p, a definition d reaches p
  - there exists a path from p to d where
    - there is not a redefinition of the var of d
  - In other words, d is not killed before it reaches p

Example: Reaching Defs

- Each basic block has
  - IN - set of definitions that reach beginning of block
  - OUT - set of definitions that reach end of block
  - GEN - set of definitions generated in block
    - Be careful about redefinitions in block
  - KILL - set of definitions killed in block
    - A statement does not kill itself!

Example: Reaching Defs

- IN[b] = OUT[b1] U ... U OUT[bn]
  - where b1, ..., bn are predecessors of b in CFG
- OUT[b] = GEN[b] U (IN[b] - KILL[b])
  - Transfer function!
- IN[entry] = 0…0

- Forward analysis
- Confluence operator: U
- Transfer function of form: f(X) = A U (X – B)
  - A = GEN, B = KILL

Analysis Information Inside Basic Blocks

- One detail:
  - Given dataflow information at IN and OUT of node
  - Also need to compute information at each statement of basic block
  - Simple propagation algorithm usually works fine
  - Can be viewed as restricted case of dataflow analysis
- Generates gen[b] and kill[b] sets for each basic blocks for reaching defs
- Might have to specialize for each analysis

Transformation Examples with Dataflow Analysis

- Global Constant Propagation and Folding
  - ~Reaching definitions
- Global Copy Propagation
  - Reaching definitions + More
- Loop Invariant Code Motion
  - Reaching definitions
- Liveness Analysis
  - Useful for register allocation

Constant Propagation

- **Constant propagation** is the process of substituting the values of known constants in expressions at compile time.

```
int x = 14;
int y = 7 - x / 2;
return y * (28 / x + 2);
```

- Applying constant propagation once yields:

```
int x = 14;
int y = 7 - 14 / 2;
return y * (28 / 14 + 2);
```

- Can apply again after folding!
- Works on your 3-address low IR.

Useful Way to Store Reaching Defs

- Use-def and Def-use chains
  - Use-Def (UD) chain lists all definitions flowing to a use of a variable
  - Def-Use (DU) chain lists all uses which can be reached by a definition
- Ex: Global Constant Propagation
  - For each use of a variable, find all definitions
  - If all definitions of the variable are constant and same value, replace the use with the constant

Copy Propagation

- **copy propagation** is the process of replacing the occurrences of targets of direct assignments with their values.
- A direct assignment is an instruction of the form x = y, which simply assigns the value of y to x.

```
x = y;
z = 3 + x
```

- Copy propagation would yield:

```
x = y
z = 3 + y
```

Copy Propagation

- For *s*: x = y, we can substitute y for x in all places, *u*, where this definition of x is used.
  - s must be only def of x reaching u
  - On every path from *s* to *u*, there are no assignments to y.
- 1 and 2 can be checked with u/d chains but with additional work.
- Can check 1 and 2 with a new dataflow analysis

Copy Propagation Analysis

- Bit-vector of all copy statements (could have multiple `x = y`)
- c_gen[B] is the copy statements generated in B
  - for x = y, x and y cannot be assigned later in the block
- c_kill[B] are the copy statements killed by B
  - `x = exp`

    kills copy statements

    `var` `= x` and `x =` *`var`* in different blocks!

Copy Propagation Analysis

- OUT[b] = c_gen[b] U (IN[b] – c_kill[b])
- IN[b] = OUT[b1] ∩ ... ∩ OUT[bn]
  - where b1, ..., bn are predecessors of b in CFG and bi is not initial
- IN[b_entry] = 0…0

- Forward analysis
- Confluence operator ∩
- Transfer function: f(X) = A U (X – B)

Copy Propagation

- After this analysis we know that if the bit for S is 1 at entry to a block B, only this copy can “reach” B.
- We can replace y with x in B.
- Whale Book 12.5.

Liveness Analysis

- For block B, let DEF[B] be the set of vars definitely assigned values in B prior to any use of that variable in B.
  - x not in DEF[{y = x + 5; x = q;}]
- Let USE[B] be the set of vars whose values may be used in B prior to any def of the var
  - x not in USE[{x = 6; y =x + 5;}]

Liveness Analysis

Liveness analysis:

- IN[b] = USE[b] U (out[b] – DEF[b])
- OUT[B] = IN[s1] U … U IN[sn]

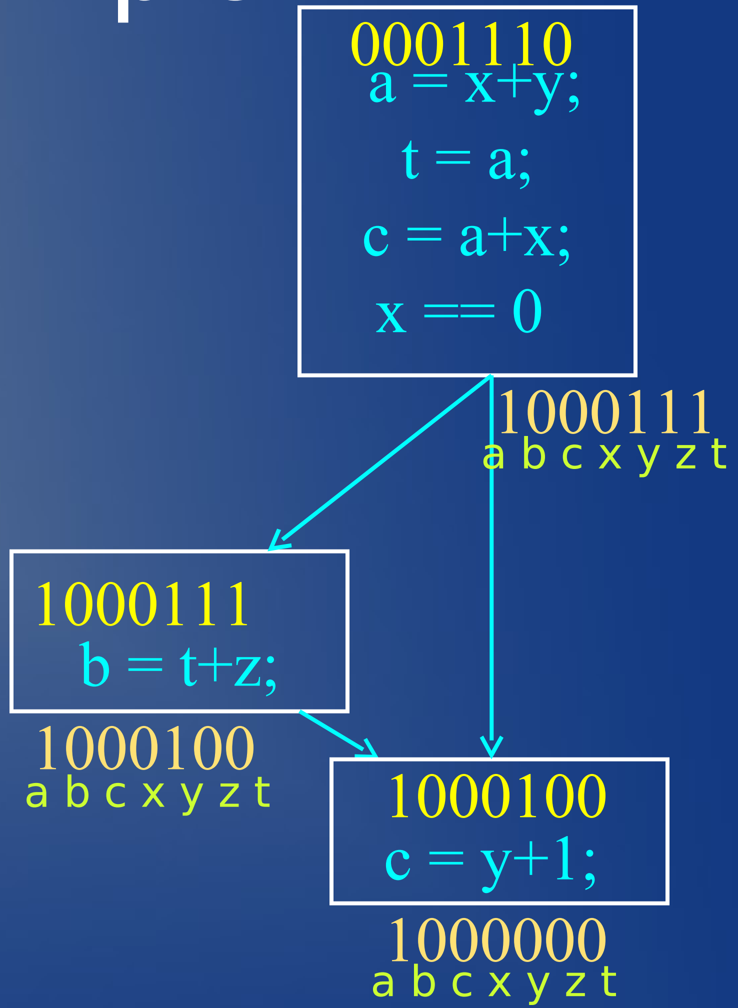
  where s1…sn are sucessors of b

- Backward analysis
- Confluence operator: U
- Transfer function: f(X) = A U (X – B)

Dead Code Elimination

- Do not use liveness analysis for DCE
- It operates on program variables not on statements!
- Consult Whale Book 18.10.
  - Requires DU and UD chains

Shortcoming of Liveness-Based DCE Example



Loop Invariant Code Motion

- Statements which could be moved before the loop or after the loop, without affecting the semantics of the program.

```
void foo(int x, int z) {
  int y;
  for a = 0, x {
     y = (x + 3) + y + bar(z);
  }
  return y;
}
```

- Difficult to get correct: see Dragon 10.7

Loop Invariant Code Motion

- UD chains (where does a value come from?)
- Control flow analysis (to figure out which definition is or is not invariant for a loop)
  - Old Dragon Book Section 10.3

General Dataflow Analysis Framework

- Build parameterized dataflow analyzer once, use for all dataflow problems
  - should work on all your IRs
- Commonalities:
  - Transfer function form
  - Confluence operators U and ∩
- Differences:
  - Dataflow equations A and B of transfer function
  - The exact confluence operator
  - Forward or backward

General
Dataflow Analysis Framework

- Questions:
  - How are arrays handled?
    - Handle elements individually for more information (when you know the information)
  - Globals:
    - How are function calls handled?
    - What can a function call do to global variables?

Common Sub-Expression Elimination

- if *x* ***o*** *y* is computed more than once, can we eliminate one of the computations
- Might not always be profitable
  - increases register pressure
  - more memory accesses (versus ALU ops)
- For local transformation (within a basic block), we can use value numbering
  - See lecture
- For global (intra-procedural) CSE, we leverage dataflow analysis
  - Available expressions

Available Expressions

- Expression x **o** y is *available* at point p if
  - on **every** path to p, x **o** y is computed and
  - neither x nor y are redefined since the most recent x **o** y on a path
- Scan function for all expressions and create a bit vector to represent them
  - Should be simple if using quadruples

Formalizing Analysis

- Each basic block has
  - IN - set of expressions available at start of block
  - OUT - set of expressions available at end of block
  - GEN - set of expressions computed in block
    - generated in block and operands not redefined after
    - Scan block from beginning to end:
      - add expressions evaluated
      - delete expressions whose operands are assigned
      - be careful with a = a + b
  - KILL - set of expressions killed in in block
    - generated in other block but operands redefined in this block
    - look for assignments and kill expressions that have an operand that is assigned

Dataflow Equations

- $IN[b] = OUT[b1] \cap \ldots \cap OUT[bn]$
  - where b1, ..., bn are predecessors of b in CFG
- $OUT[b] = (IN[b] - KILL[b]) \cup GEN[b]$
- Initialize:
  - IN[i] = 1…1 (all expressions)
  - IN[entry] = 0…0 (or 1…1 if we have special entry node)

- Forward analysis
- Confluence operator: $\cap$
- Transfer function of familiar form

Solving Equations

- Use fixed point algorithm
- IN[entry] = 0…0
- Initialize OUT[b] = 1…1
- Repeatedly apply equations
  - IN[b] = OUT[b1] $\cap$ ... $\cap$ OUT[bn]
  - OUT[b] = (IN[b] - KILL[b]) U GEN[b]
- Use a worklist algorithm to reach fixed point

Now What?

For all blocks b and expressions exp in IN[b] and evaluated in b

1. Locate occurrences in b of exp
2. make sure that none of the operands were re-defined in b previously, if so it is not a CSE
3. Find all the reaching occurrences of exp in predecessor blocks
   - Follow flow edges backwards from b
   - Don’t go through a block that evaluates exp
   - The last evaluation of exp in each block reaches b
4. Select a new temp t
   - Replace exp by t for all occurrences in b that are CSE (step 2)
   - For each instruction found in (3), a = exp replace with:

     a = exp

     t = a

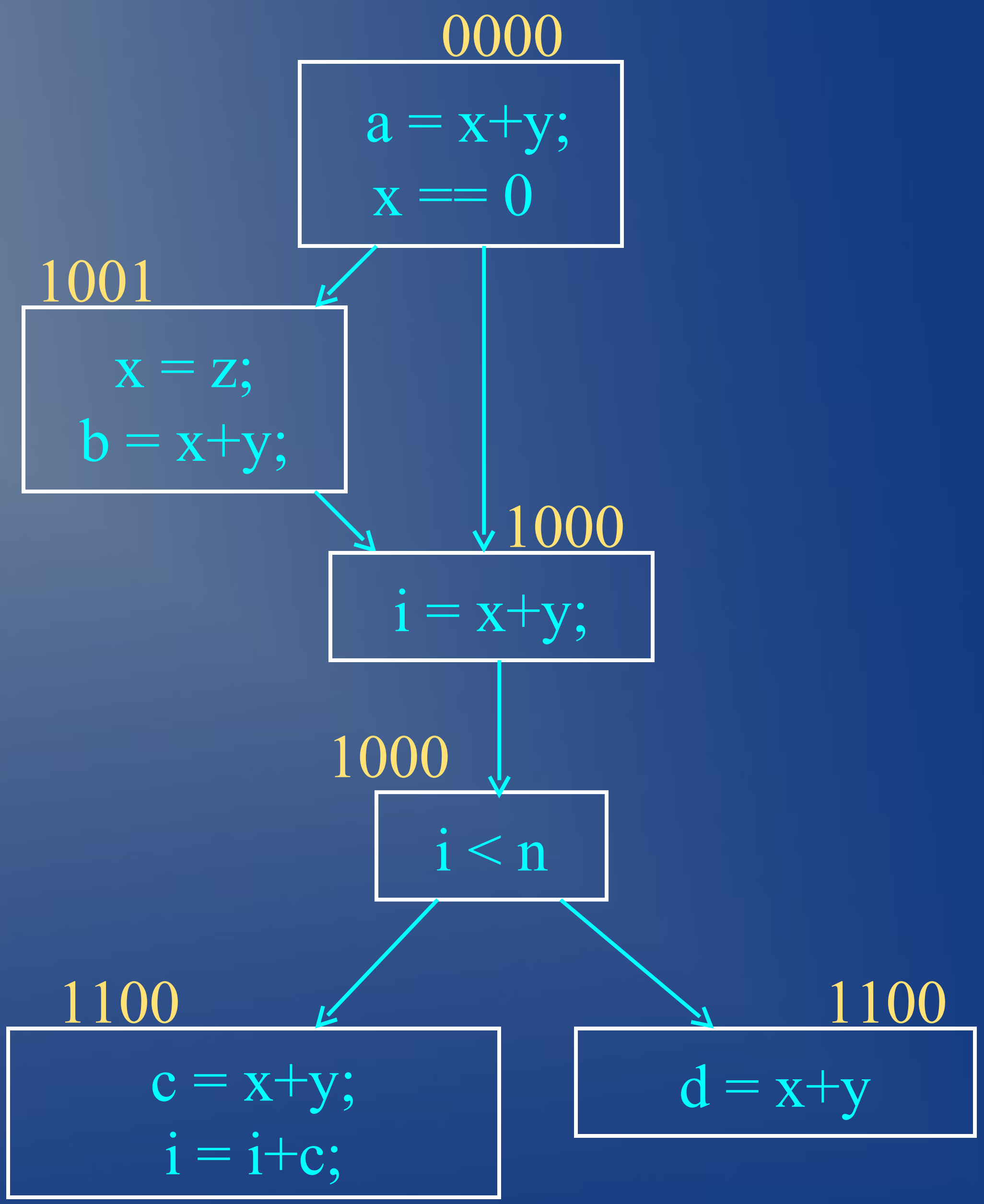
Expressions

1: x+y

2: i<n

3: i+c

4: x==0



Global CSE Transform

Expressions
1: x+y
2: i<n
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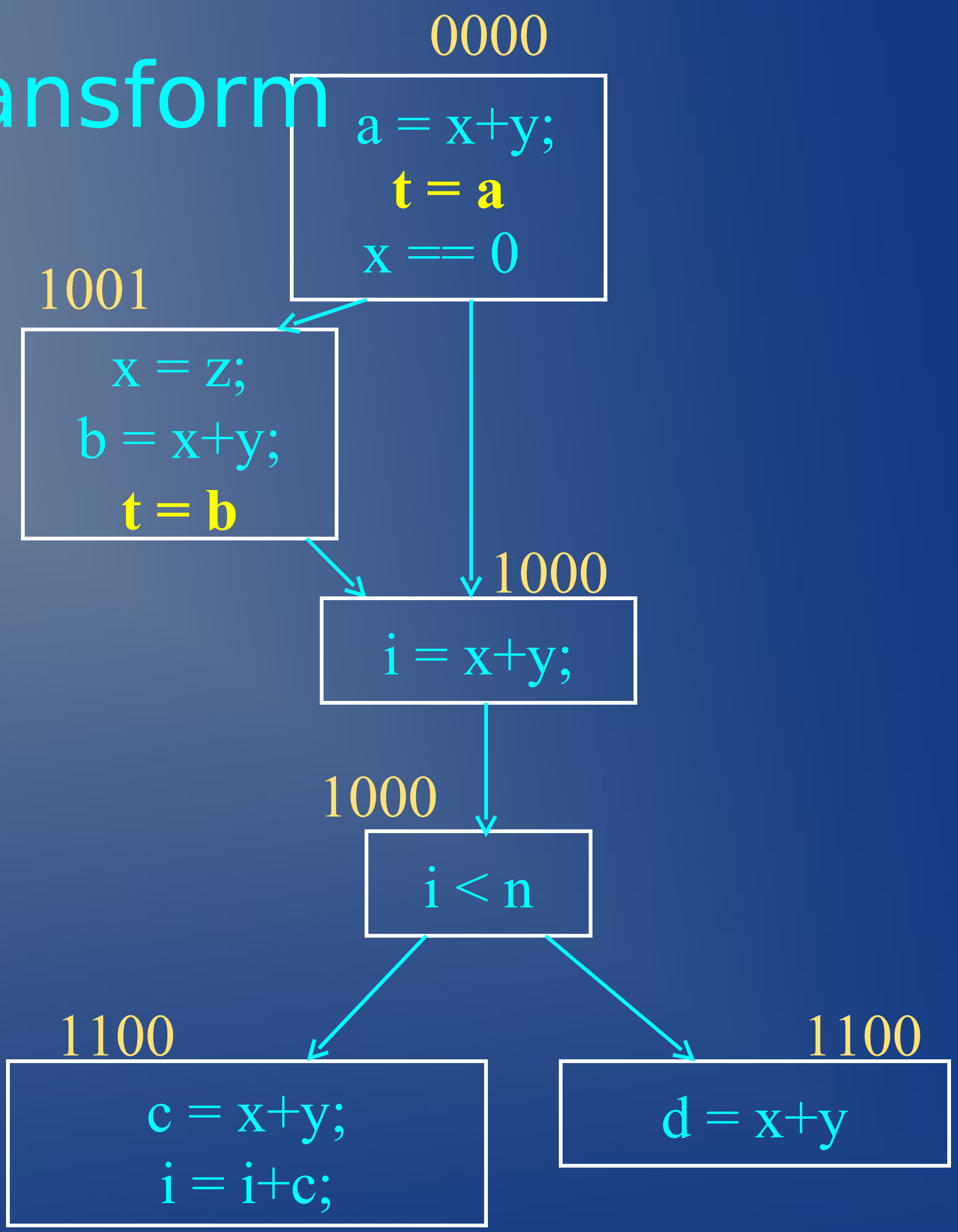
4: x==0



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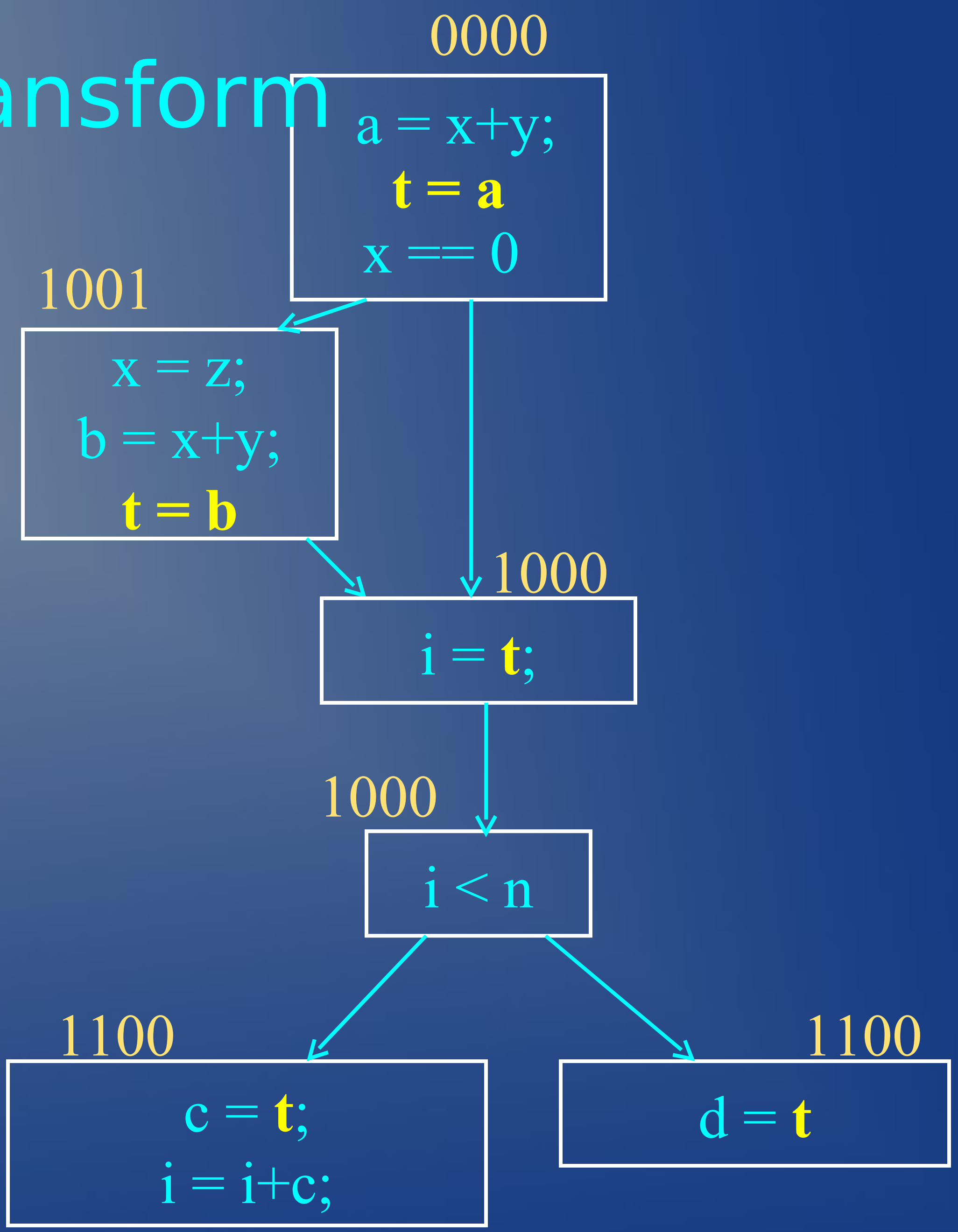

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