CS251: Introduction to Language Processing

Machine Independent Optimizations

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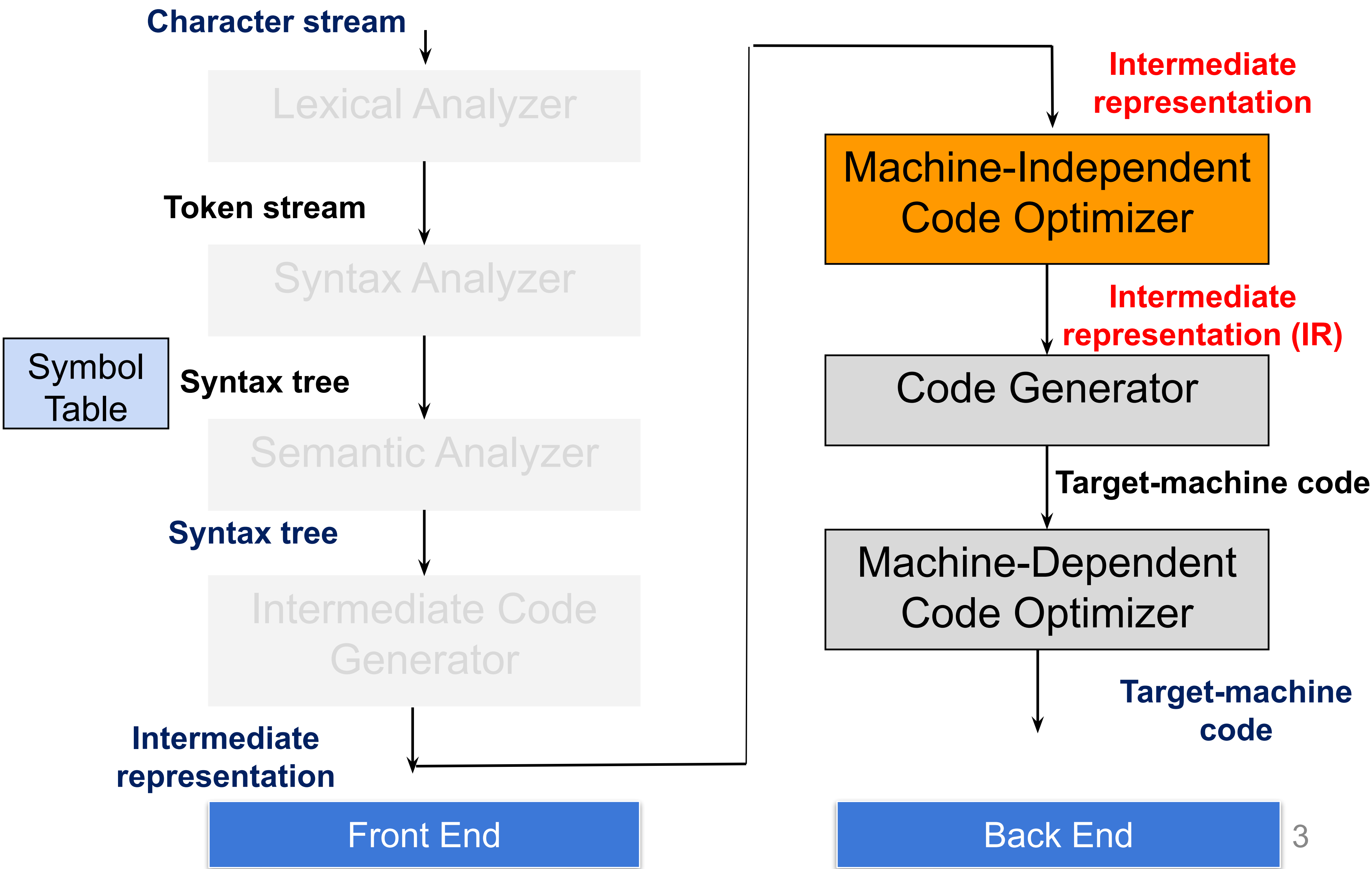
2023-24 M

Acknowledgement

- References for today's slides
  - *Stanford University*
    https://web.stanford.edu/class/archive/cs/cs143/cs143.1128/
  - *Prof. Y. N Srikant, IISc Bangalore*
    https://iith.ac.in/~ramakrishna/Compilers-Aug14/slides/
  - *http://sei.pku.edu.cn/~yaoguo/ACT11/slides/lect2-opt.ppt*
  - *Course textbook*

Compiler Design



Why IR Optimization?

- In order to optimize our IR, we need to understand why it can be improved in the first place.
- **Reason one:** IR generation introduces redundancy.
  - A naïve translation of high-level language features into IR often introduces sub computations.
  - Those sub computations can often be speeded up or eliminated.
- **Reason two:** Programmers are lazy.
  - Code executed inside of a loop can often be factored out of the loop.

Optimizations from IR Generation

```
int x;
int y;
bool b1;
bool b2;
bool b3;

b1 = x * x + y
b2 = x * x - y
b3 = x * x * y
```

Optimizations from IR Generation

```
int x;
int y;
bool b1;
bool b2;
bool b3;

b1 = x * x + y
b2 = x * x - y
b3 = x * x * y
```

```
t0 = x * x;
t1 = t0 + y;
b1 = t1

t2 = x * x;
t3 = t2 - y;
b2 = t3

t4 = x * x;
t5 = t4 * y;
b3 = t4
```

Optimizations from IR Generation

```
int x;
int y;
bool b1;
bool b2;
bool b3;

b1 = x * x + y
b2 = x * x - y
b3 = x * x * y
```

```
t0 = x * x;
t1 = t0 + y;
b1 = t1

t2 = x * x;
t3 = t2 - y;
b2 = t3

t4 = x * x;
t5 = t4 * y;
b3 = t4
```

Optimizations from IR Generation

```
int x;
int y;
bool b1;
bool b2;
bool b3;

b1 = x * x + y
b2 = x * x - y
b3 = x * x * y
```

```
t0 = x * x;
t1 = t0 + y;
b1 = t1

t2 = t0 - y;
b2 = t2

t3 = t0 * y;
b3 = t3
```

```
while (x < y + z) {
    x = x - y;
}
```

Optimizations from Lazy Coders

```
while (x < y + z) {
    x = x - y;
}
```

```
L0:
    t0 = y + z;
    If x < t0 Goto L1;
    t1 = x - y;
    x = t1
    Goto L0;
L1:
```

Optimizations from Lazy Coders

```
while (x < y + z) {
    x = x - y;
}
```

```
L0:
    t0 = y + z;
    If x < t0 Goto L1;
    t1 = x - y;
    x = t1
    Goto L0;
L1:
```

Optimizations from Lazy Coders

```
while (x < y + z) {
    x = x - y;
}
```

```
    t0 = y + z;
L0:
    If x < t0 Goto L1;
    t1 = x - y;
    x = t1
    Goto L0;
L1:
```

A Note on Terminology

- The term "optimization" implies looking for an "optimal" piece of code for a program.
- This is, in general, undecidable.
- Our goal will be IR *improvement* rather than IR *optimization*.

The Challenge of Optimization

- A good optimizer
  - Should never change the observable behavior of a program.
  - Should produce IR that is as efficient as possible.
  - Should not take too long to process inputs.
- Unfortunately:
  - Optimizers often miss "easy" optimizations due to limitations of their algorithms.
  - Almost all interesting optimizations are NP-hard or undecidable.

What are we Optimizing?

- Optimizers can try to improve code usage with respect to many observable properties.
- What are some quantities we might want to optimize?

What are we Optimizing?

- Optimizers can try to improve code usage with respect to many observable properties.
- What are some quantities we might want to optimize?
- **Runtime** (make the program as fast as possible at the expense of time and power)
- **Memory usage** (generate the smallest possible executable at the expense of time and power)
- **Power consumption** (choose simple instructions at the expense of speed and memory usage)
- Plus a lot more (minimize function calls, reduce use of floating-point hardware, etc.)

Overview of IR Optimization

- **Formalisms and Terminology** (Today)
  - Control-flow graphs.
  - Basic blocks.
- **Optimizations** (Today)
  - Examples
- **Data flow analysis** (Next lecture)
  - Implementation point of view in compiler

Formalisms and Terminology

Semantics-Preserving Optimizations

- An optimization is **semantics-preserving** if it does not alter the semantics of the original program.
- Examples:
  - Eliminating unnecessary temporary variables.
  - Computing values that are known statically at compile-time instead of runtime.
  - Evaluating constant expressions outside of a loop instead of inside.
- Non-examples:
  - Replacing bubble sort with quicksort.
- The optimizations we will consider in this class are all semantics-preserving.

A Formalism for IR Optimization

- Every phase of the compiler uses some new abstraction:
  - Scanning uses regular expressions.
  - Parsing uses CFGs.
  - Semantic analysis semantic actions and symbol tables.
  - Intermediate code generation uses IRs.
- In optimization, we need a formalism that captures the structure of a program in a way amenable to optimization.

Examples

```
1)   i = 1
2)   j = 1
3)   t1 = 10 * i
4)   t2 = t1 + j
5)   t3 = 8 * t2
6)   t4 = t3 - 88
7)   a[t4] = 0.0
8)   j = j + 1
9)   if j <= 10 goto (3)
10)  i = i + 1
11)  if i <= 10 goto (2)
12)  i = 1
13)  t5 = i - 1
14)  t6 = 88 * t5
15)  a[t6] = 1.0
16)  i = i + 1
17)  if i <= 10 goto (13)
```

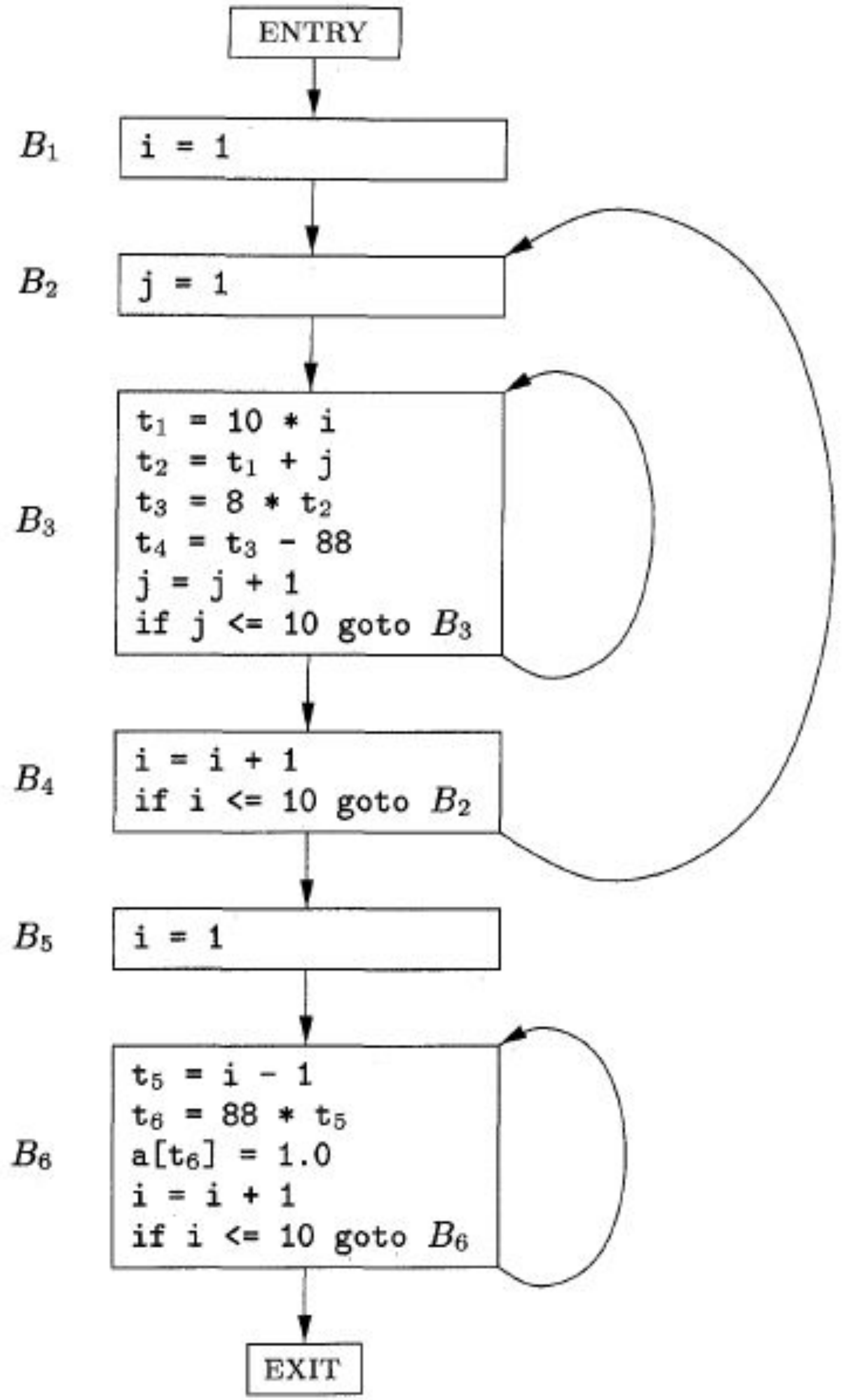
```
for i from 1 to 10 do
  for j from 1 to 10 do
     a[i,j]=0.0

for i from 1 to 10 do
     a[i,i]=0.0
```

Control Flow

```
for i from 1 to 10 do
  for j from 1 to 10 do
    a[i,j]=0.0

for i from 1 to 10 do
    a[i,i]=0.0
```



Basic Blocks

- A **basic block** is a maximal sequence of consecutive three-address instructions with the following properties:
  - The flow of control can only enter the basic block thru the 1st instr.
  - There is exactly one spot where control leaves the sequence, which must be at the end of the sequence.
- Basic blocks become the nodes of a **flow graph**, with edges indicating the order.

Identifying Basic Blocks

- Input: sequence of instructions *instr(i)*
- Output: A list of basic blocks
- Method:
  - Identify **leaders**:

    the first instruction of a basic block
  - Iterate: add subsequent instructions to basic block until we reach another leader

Identifying Leaders

- Rules for finding leaders in code
  - First instr in the code is a leader
  - Any instr that is the target of a (conditional or unconditional) jump is a leader
  - Any instr that immediately follow a (conditional or unconditional) jump is a leader

Basic Block Partition Algorithm

```
leaders = {1}              // start of program
for i = 1 to |n|           // all instructions
    if instr(i) is a branch
     leaders = leaders U  targets of instr(i) U  instr(i+1)
worklist = leaders
While worklist not empty
    x = first instruction in worklist
    worklist = worklist – {x}
    block(x) = {x}
    for i = x + 1; i <= |n| && i not in leaders; i++
     block(x) = block(x) U {i}
```

Basic Block Example

```
1.  i = 1                    A
2.  j = 1                    B
3.  t1 = 10 * i
4.  t2 = t1 + j
5.  t3 = 8 * t2
6.  t4 = t3 - 88             C
7.  a[t4] = 0.0
8.  j = j + 1
9.  if j <= 10 goto (3)
10. i = i + 1
11. if i <= 10 goto (2)      D
12. i = 1                    E
13. t5 = i - 1
14. t6 = 88 * t5
15. a[t6] = 1.0              F
16. i = i + 1
17. if i <= 10 goto (13)
```

Leaders

Basic Blocks

Control Flow Graphs

- **Control-flow graph**:
  - Node: an instruction or sequence of instructions (a basic block)
    - Two instructions i, j in same basic block *iff* execution of i *guarantees* execution of j
  - Directed edge: *potential* flow of control
  - Distinguished start node *Entry & Exit*
    - First & last instruction in program

Control Flow Edges

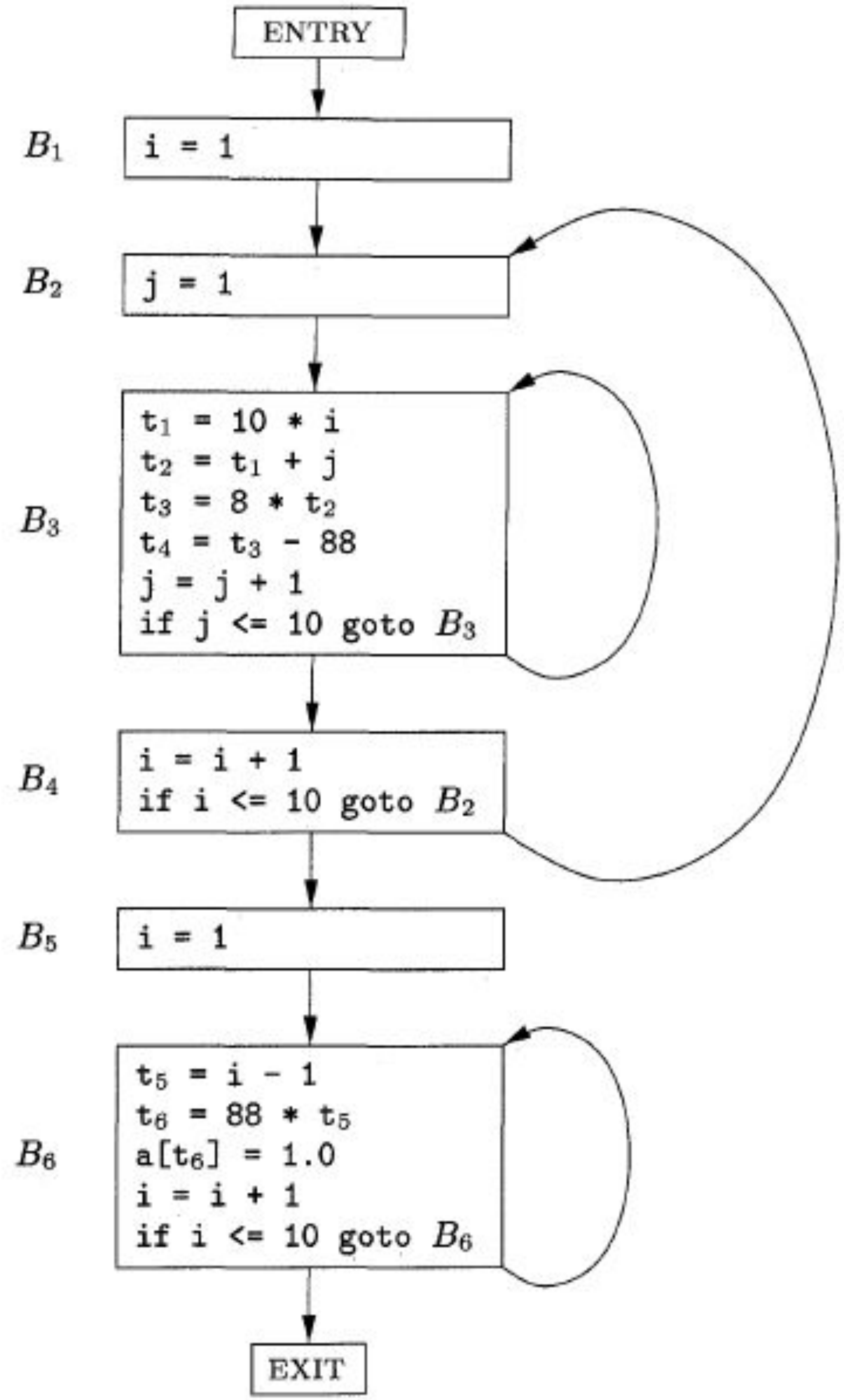
- Basic blocks = nodes
- Edges:
  - Add directed edge between B1 and B2 if:
    - Branch from last statement of B1 to first statement of B2 (B2 is a leader), or
    - B2 immediately follows B1 in program order and B1 does not end with unconditional branch (goto)
  - Definition of predecessor and successor
    - B1 is a predecessor of B2
    - B2 is a successor of B1

Control Flow Algorithm

Input: block(i), sequence of basic blocks
Output: CFG where nodes are basic blocks

```
for i = 1 to the number of blocks
    x = last instruction of block(i)
    if instr(x) is a branch
     for each target y of instr(x),
          create edge (i -> y)
    if instr(x) is not unconditional branch,
     create edge (i -> i+1)
```

CFG Example



ENTRY
B_1
i = 1
B_2
j = 1
B_3
t_1 = 10 * i
t_2 = t_1 + j
t_3 = 8 * t_2
t_4 = t_3 - 88
j = j + 1
if j <= 10 goto B_3
B_4
i = i + 1
if i <= 10 goto B_2
B_5
i = 1
B_6
t_5 = i - 1
t_6 = 88 * t_5
a[t_6] = 1.0
i = i + 1
if i <= 10 goto B_6
EXIT

Optimizations

- Global common subexpression elimination
- Copy propagation
- Constant propagation and constant folding
- Loop invariant code motion
- Induction variable elimination and strength reduction

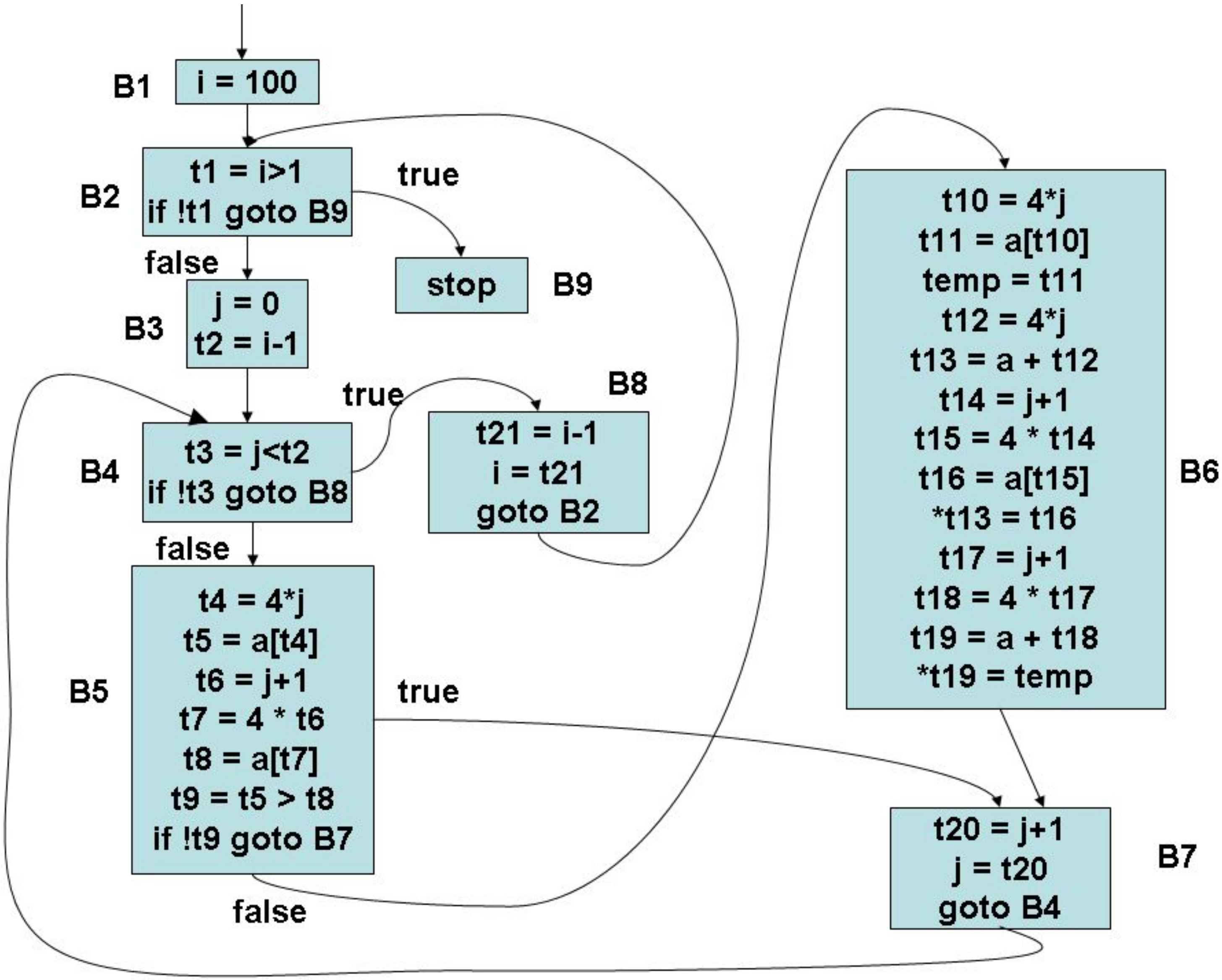
Example

Bubble Sort

```
for (i=100; i>1; i--) {
    for (j=0; j<i-1; j++) {
        if (a[j] > a[j+1]) {
            temp = a[j];
            a[j+1] = a[j];
            a[j] = temp;
        }
    }
}
```

- int a[100]
- array a runs from 0 to 99
- No special jump out if array is already sorted

Control Flow Graph of Bubble Sort



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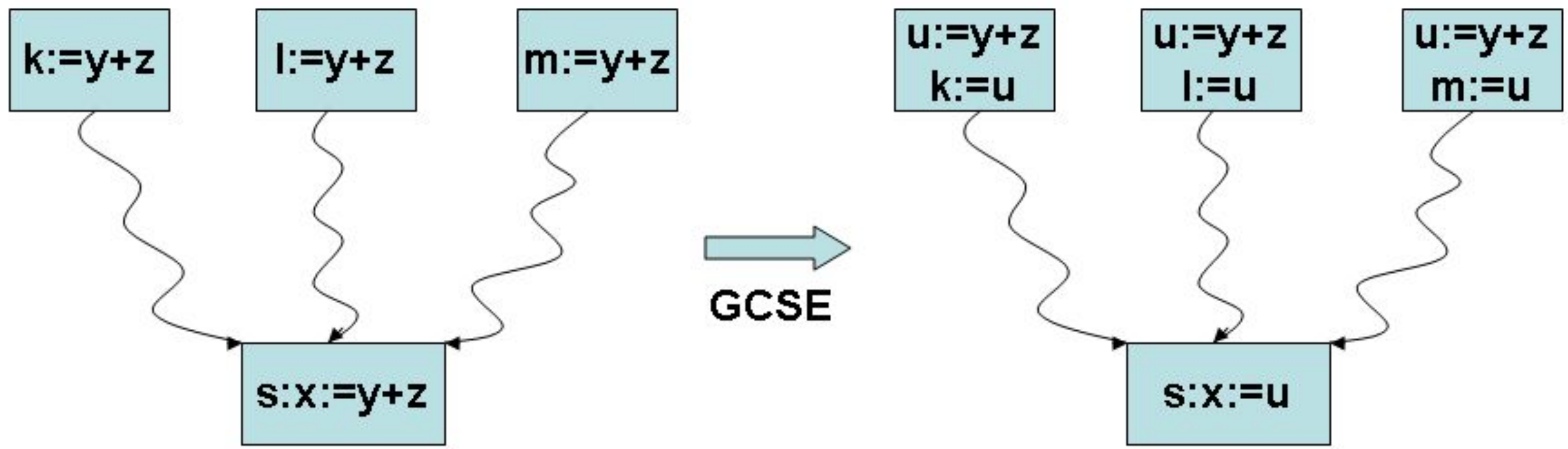
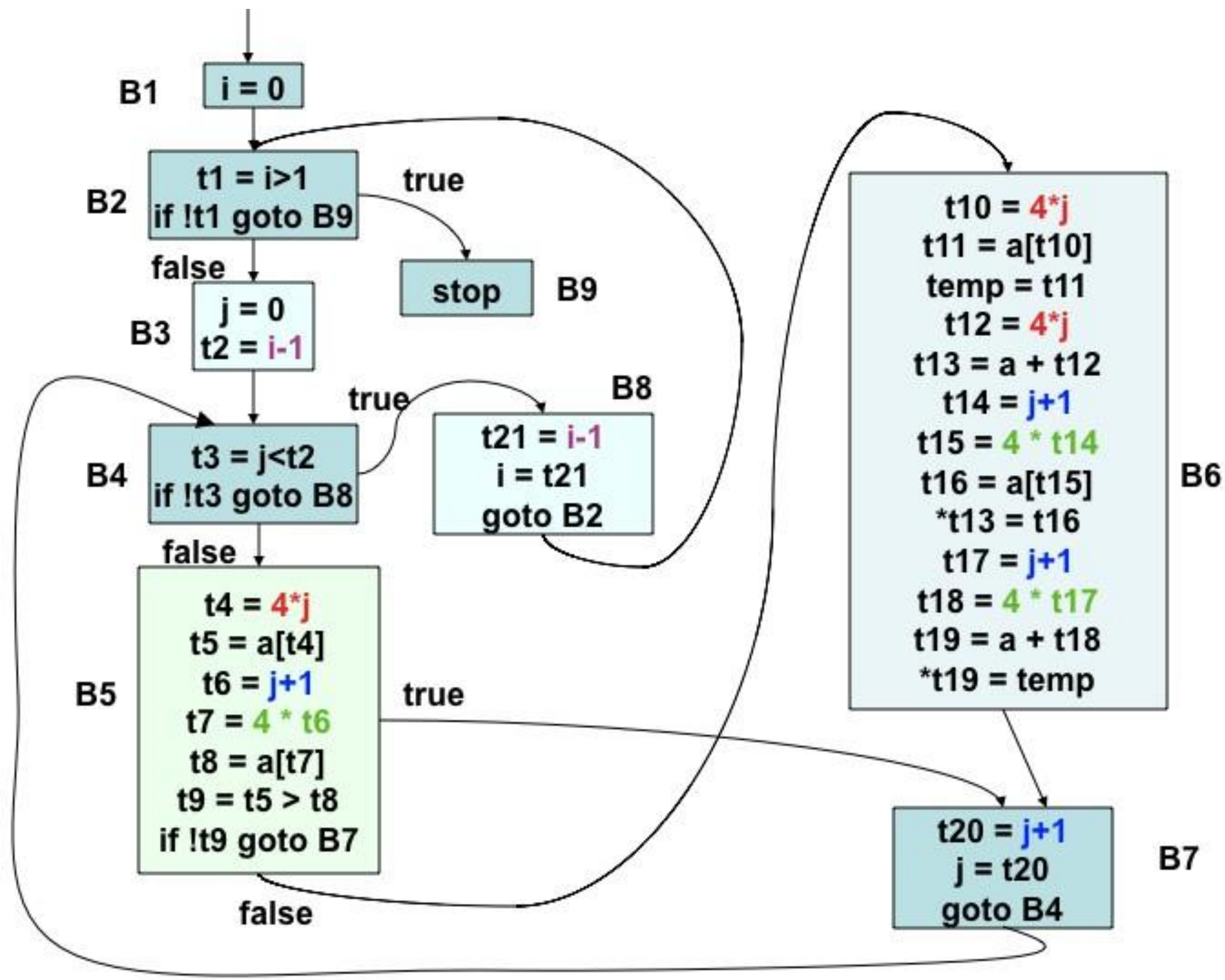
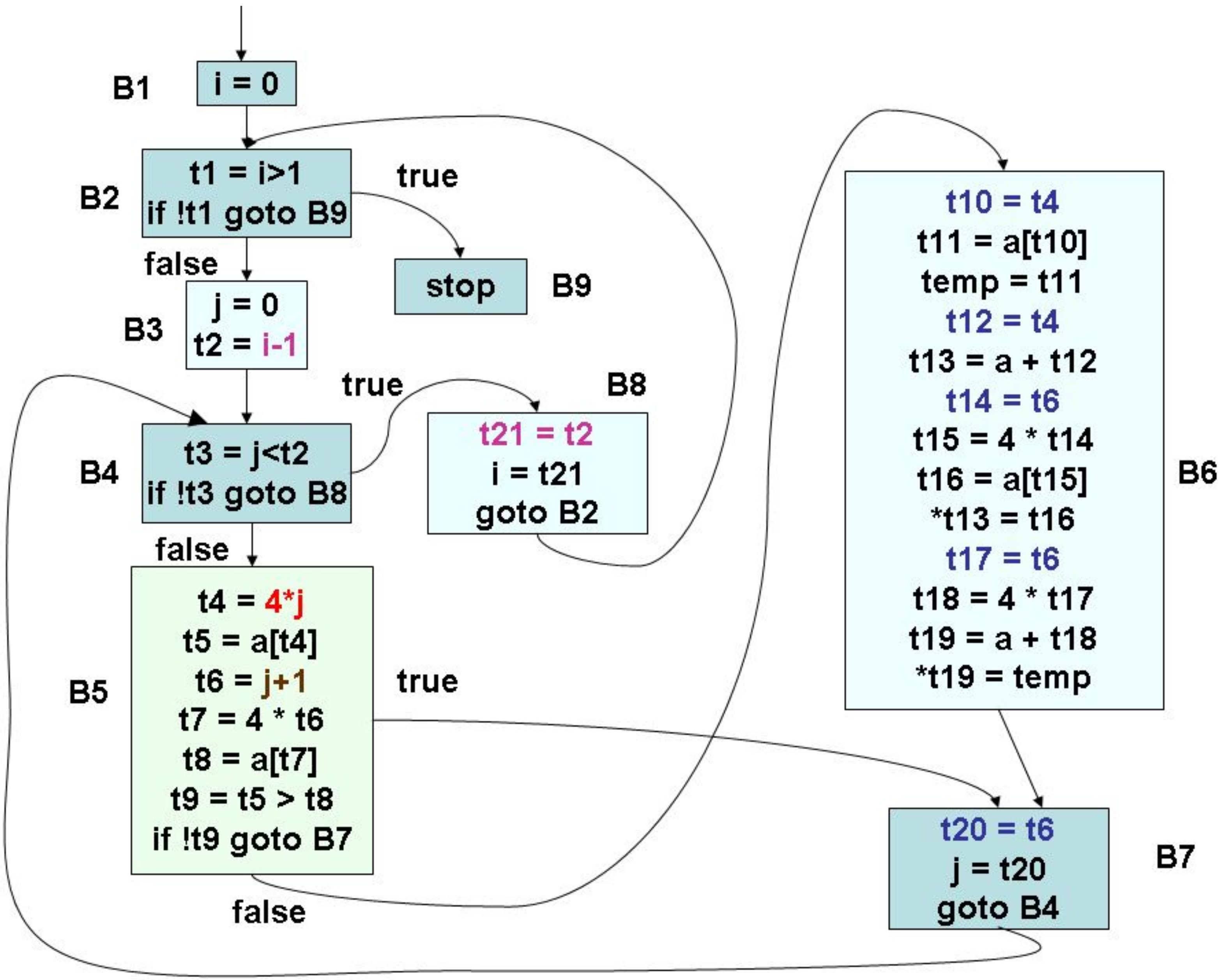
Global Common Subexpression Elimination (GCSE)



Global Common Subexpression Elimination (GCSE)



Global Common Subexpression Elimination (GCSE)



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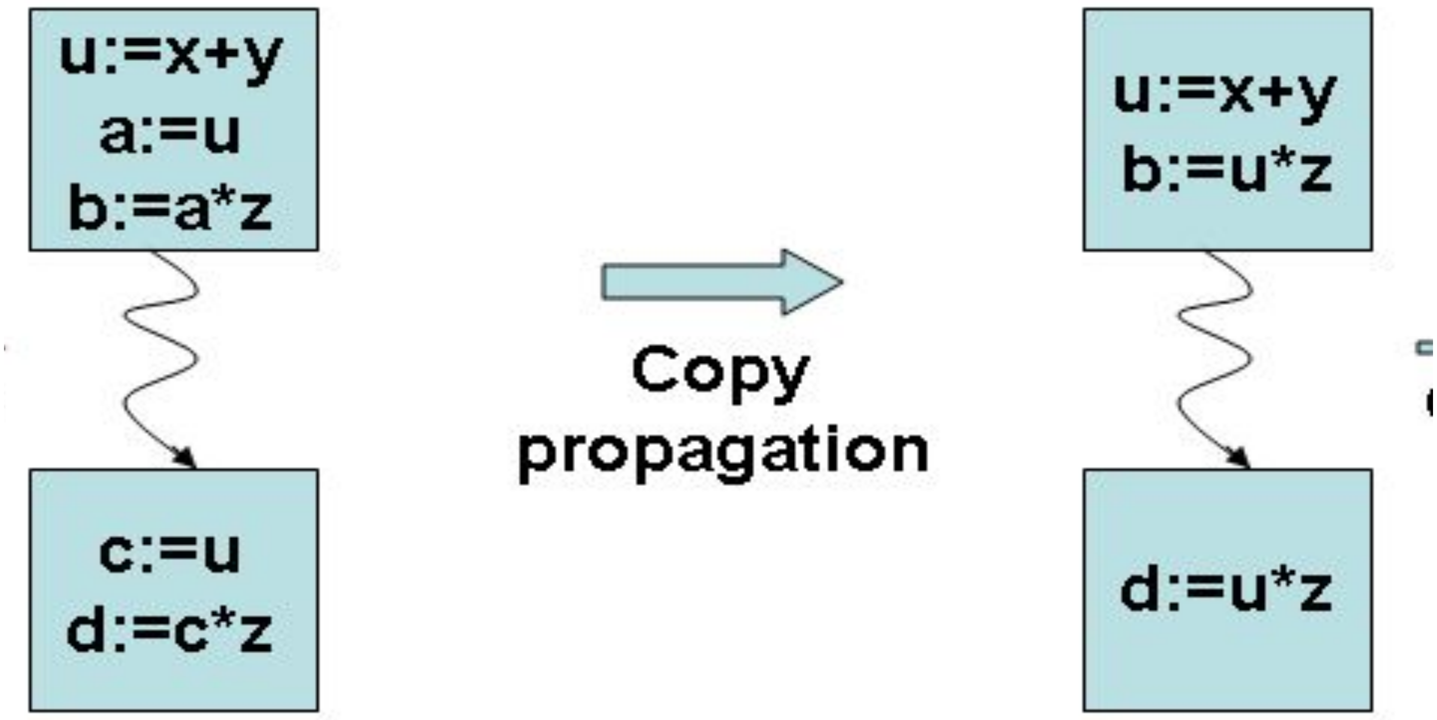
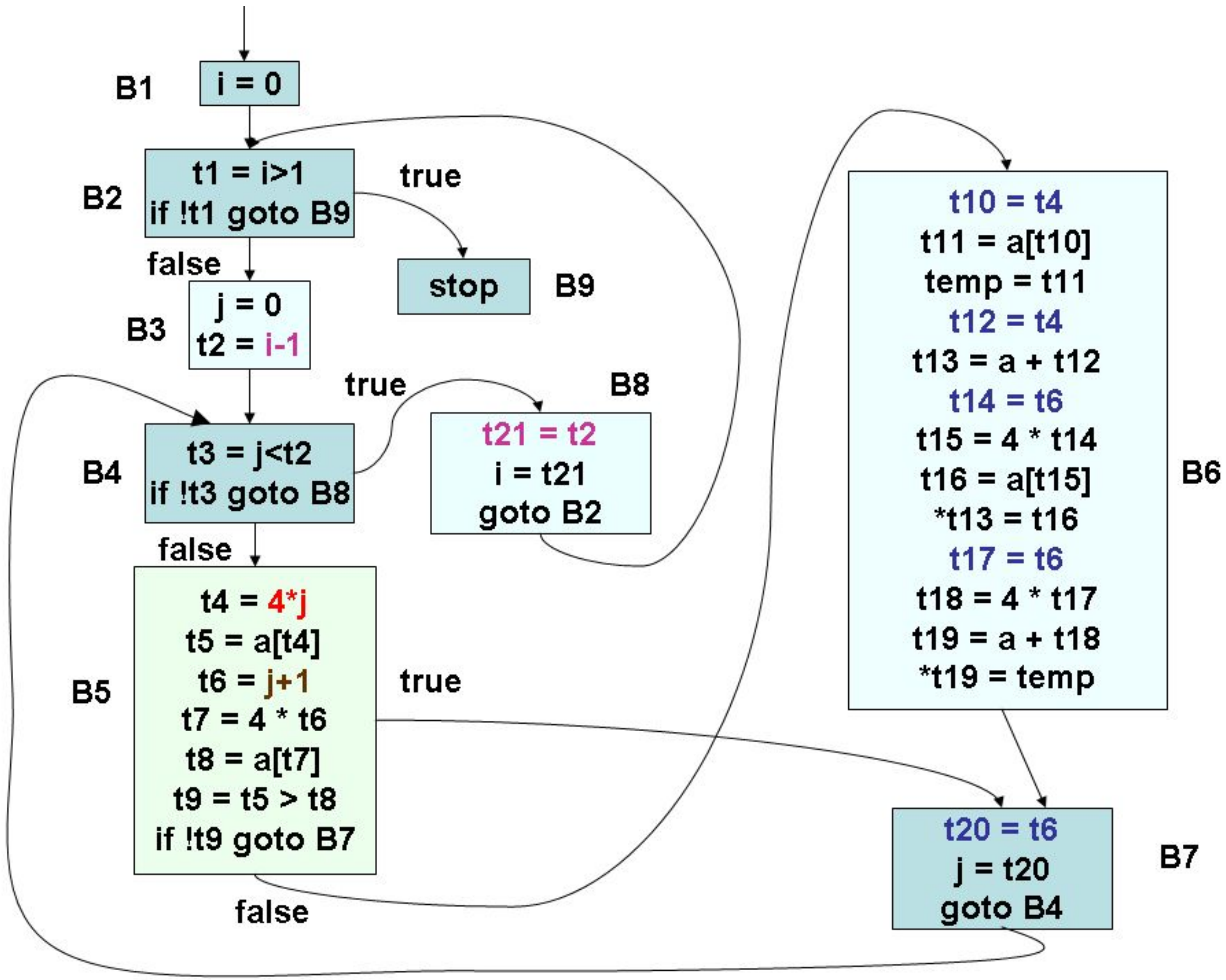
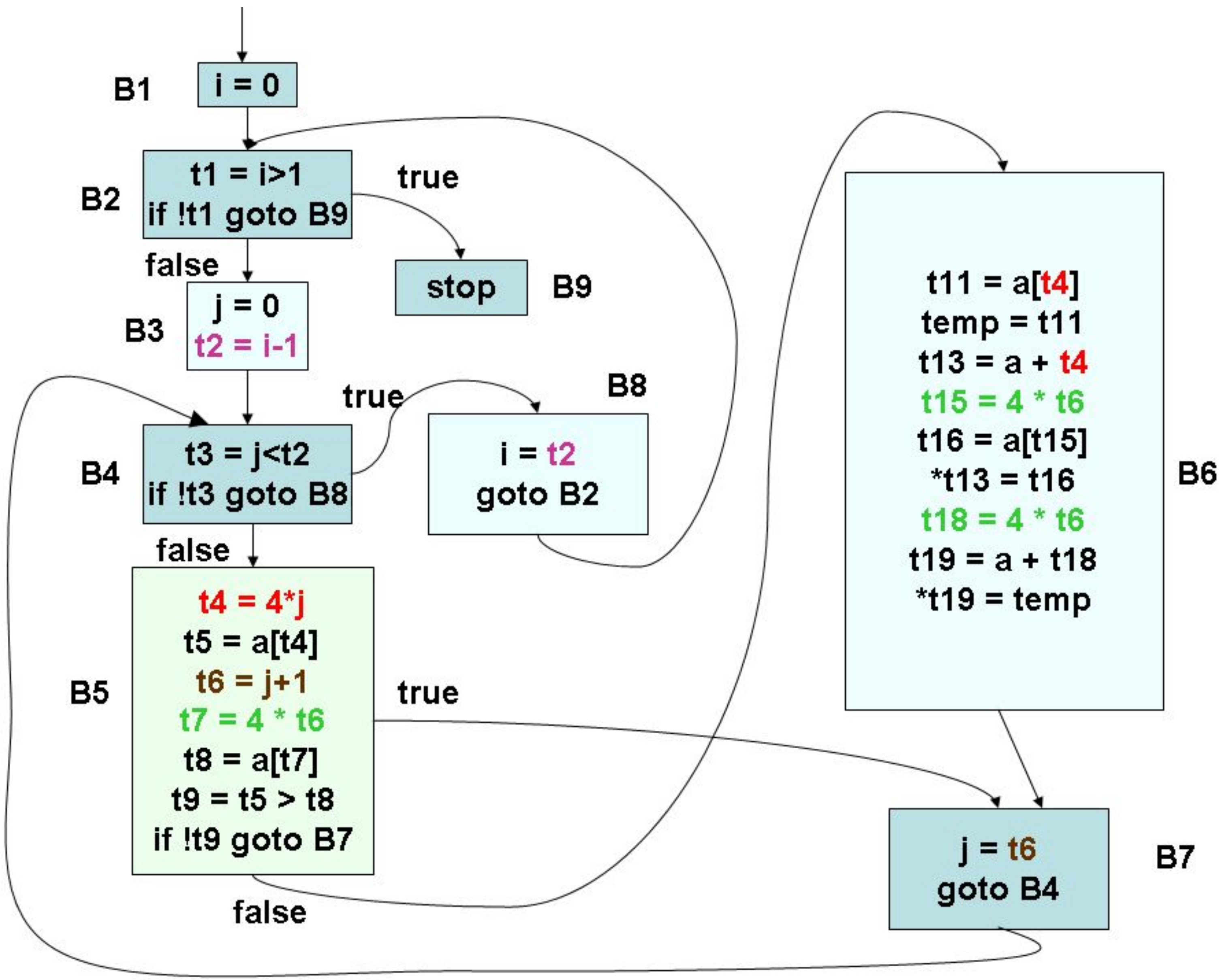
Copy Propagation



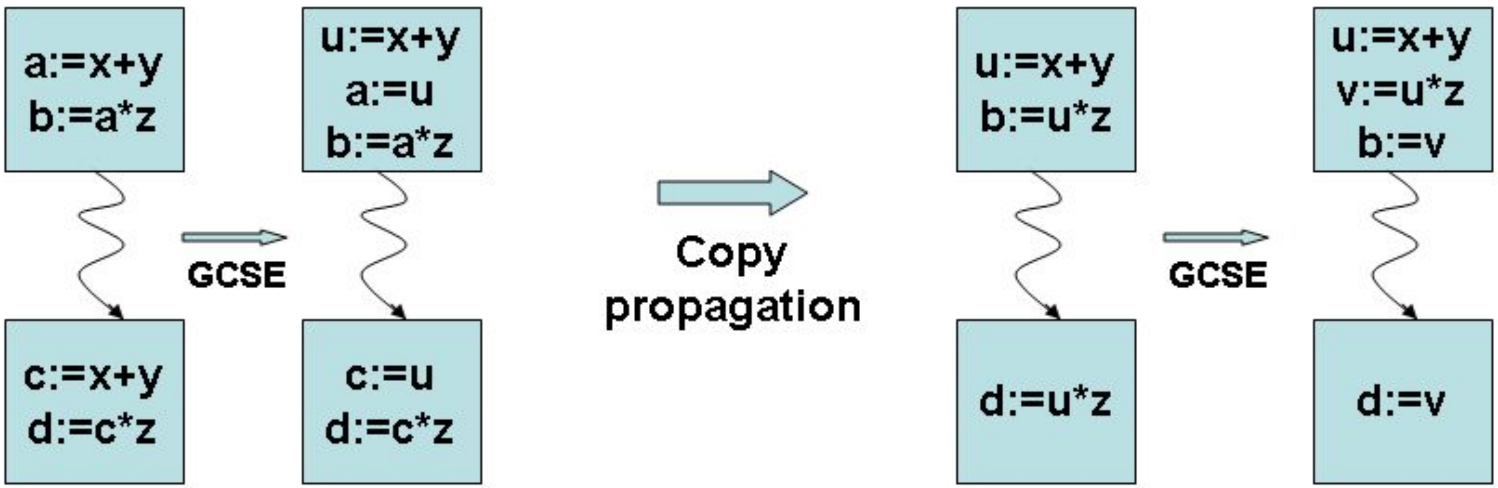
Global Common Subexpression Elimination (GCSE)



Copy Propagation

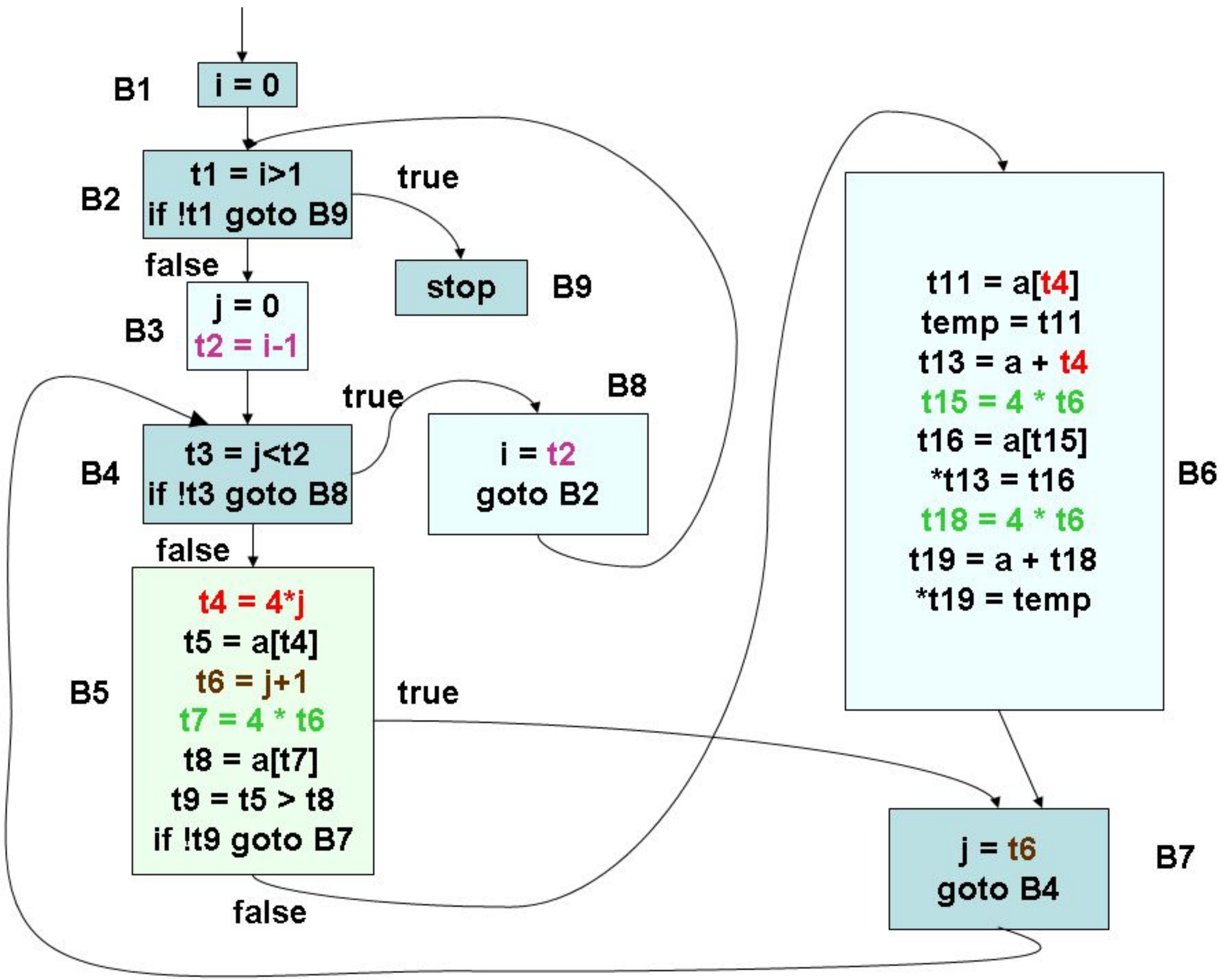


GCSE and Copy Propagation

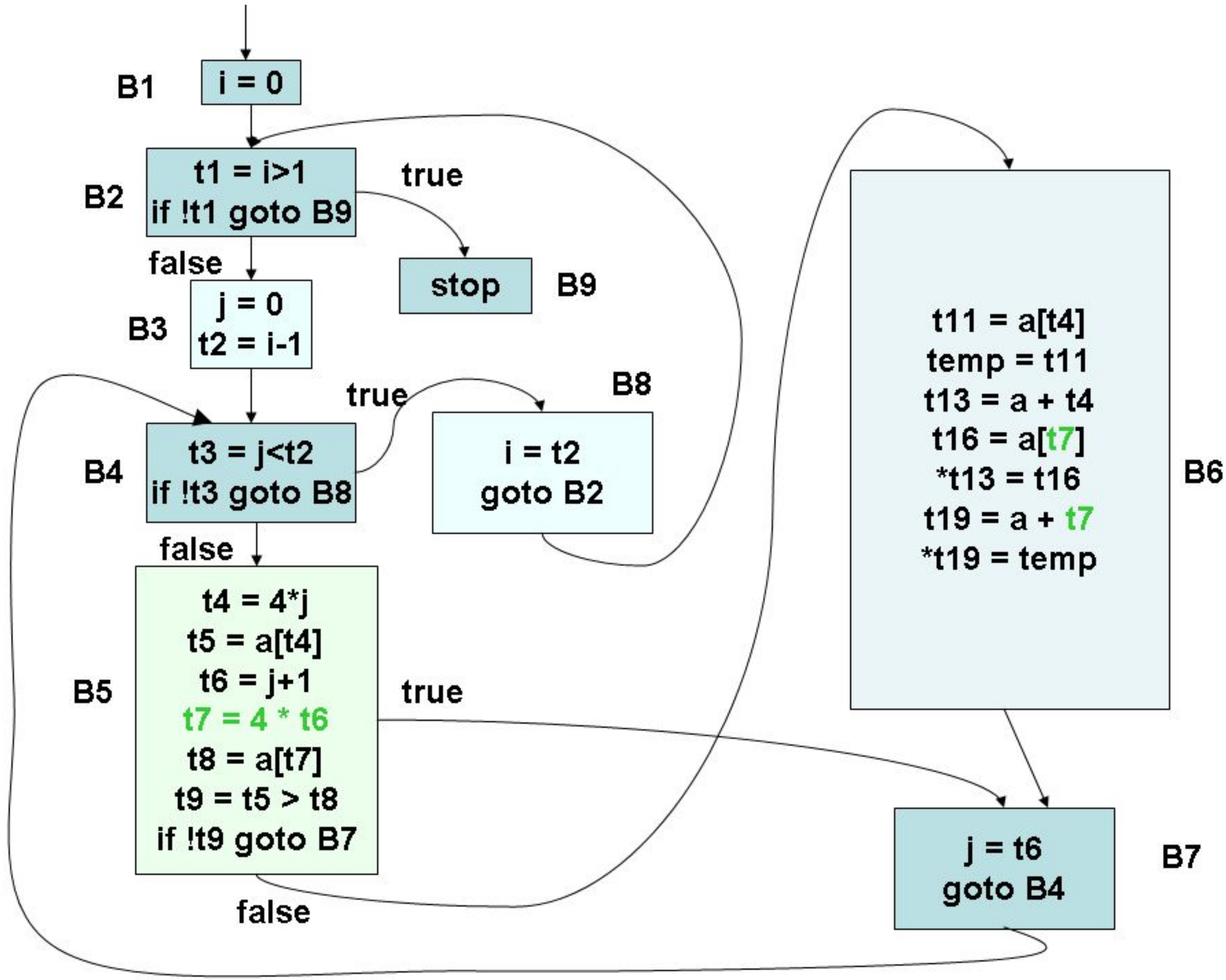


Demonstrating the need for repeated application of GCSE

GCSE and Copy Propagation



GCSE and Copy Propagation



Optimizations

- Global common subexpression elimination
- Copy propagation
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Copy Propagation and Constant Folding