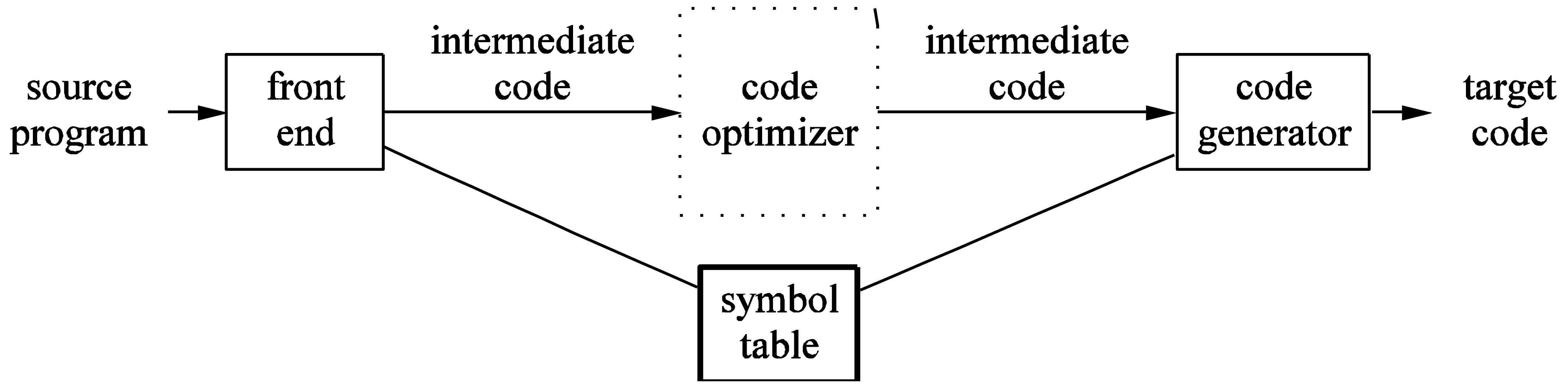
Exercises

```
int i=1,j=2,a,b=2,c=3;
if (i<j)
   a=b+c;
else
   a=b-c;
```

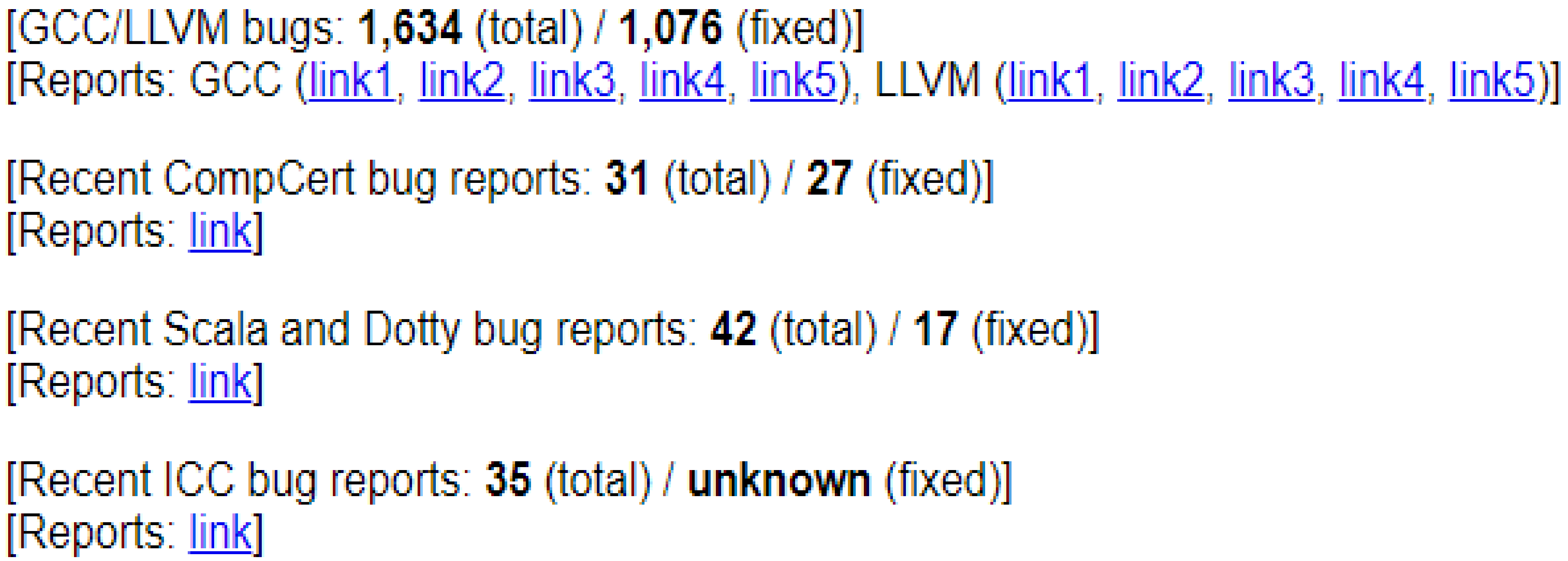
Generate its assembly code

```
ST #1, 4[FP]
ST #2, 8[FP]
ST #2, 16[FP]
ST #3, 20[FP]
LD R0, 4[FP]
LD R1, 8[FP]
CMP R0, R1
If<  goto  L
LD R0, 16[FP]
LD R1, 20[FP]
SUB R0, R0, R1
ST R0, 12[FP]
JMP END
L:
LD R0, 16[FP]
LD R1, 20[FP]
ADD R0, R0, R1
ST R0, 12[FP]
END:
```

Code Optimization



Optimizations



[GCC/LLVM bugs: **1,634** (total) / **1,076** (fixed)]
[Reports: GCC (link1, link2, link3, link4, link5), LLVM (link1, link2, link3, link4, link5)]

[Recent CompCert bug reports: **31** (total) / **27** (fixed)]
[Reports: link]

[Recent Scala and Dotty bug reports: **42** (total) / **17** (fixed)]
[Reports: link]

[Recent ICC bug reports: **35** (total) / **unknown** (fixed)]
[Reports: link]

EMI-based Compiler Testing

Optimizations

For languages like C and C++ there are three granularities of optimizations

Complexity

1. Local optimizations
   - Apply to a basic block in isolation
2. Global optimizations
   - Apply to a control-flow graph (method body) in isolation
3. Inter-procedural optimizations
   - Apply across method boundaries

powerful

Most compilers do (1), many do (2), few do (3)

Cost of Optimizations

- In practice, a conscious decision is made not to implement the fanciest optimization known

- Why?
  - Some optimizations are hard to implement
  - Some optimizations are costly in compilation time
  - Some optimizations have low benefit, no theoretic guarantee
  - Many fancy optimizations are all three!

Goal: Maximum benefit for minimum cost

Local Optimizations

- The simplest form of optimizations
- No need to analyze the whole procedure body
  - Just the basic block in question
- Techniques
  1. Algebraic Simplification
  2. Constant Folding
  3. Dead Code Elimination
  4. Common Subexpression Elimination
  5. Copy Propagation
- Each local optimization does little by itself
- Typically optimizations interact, performing one optimization enables another
- Optimizing compilers repeat optimizations until no improvement is possible

Basic Blocks

- A basic block is a sequence of statements such that:
  - Flow of control enters at start
  - Flow of control leaves at end
  - No possibility of halting or branching except at end
- Each basic block has a first statement known as the "leader" of the basic block
- A name is "live" at a given point if its value will be used again in the program
- Useful for local optimization

Transformations on Basic Blocks

- A basic block computes a set of expressions
  - The expressions are the values of names that are live on exit from the block
  - Two basic blocks are equivalent if they compute the same set of expressions
- Certain transformations can be applied without changing the computed expressions of a block
  - An optimizer uses such transformations to improve running time or space requirements of a program

Algebraic Simplification

- Some statements can be deleted
  - x := x + 0
  - x := x * 1
- Some statements can be simplified
  - x := x * 0 ⇒ x := 0
  - x := x * 2 ⇒ x := x + x
  - x := x ** 2 ⇒ x := x * x
  - x := x * 8 ⇒ x := x << 3
  - x := x * 15 ⇒ t := x << 4; x := t – x

(on some machines << is faster than *, and +/- is faster than *; but not on all!)

Constant Folding

- Operations on constants can be computed at compile time
  - If there is a statement x := y op z and y and z are constants
  - Then y op z can be computed at compile time

- Eg.
  - **x := 2+3** **⇒ x := 5**
  - **x := 2*3** **⇒ x := 6**
  - **if 2 < 0 jump L** **⇒ if false jump L** **⇒ delete**

Dead Code Elimination

- Eliminate unreachable basic blocks:
  - Code that is unreachable from the initial block
  - Is it possible?

- Removing unreachable code makes the program smaller
  - and sometimes also faster

Common Subexpression Elimination

- Common subexpression elimination (DAG):

```
a := b + c
b := a - d
c := b + c
d := a - d
```

$\Rightarrow$

```
a := b + c
b := a - d
c := b + c
d := b
```

- SSA form basic block without DAG

```
x := y + z              x := y + z
      …        ⇒          … no change of x,y,z
w := y + z              w := x
```

- Take care of points, array, function calls

Copy Propagation

- If w := x appears in a block, replace subsequent uses of w with uses of x
  - Assumes SSA form
- Example:

```
b := z + y                  b := z + y
a := b          ⇒           a := b
x := 2 * a                  x := 2 * b
```

- Only useful for enabling other optimizations
  - Constant folding
  - Dead code elimination

Examples

- Copy Propagation and Constant Folding

```
a := 5                 a := 5
x := 2 * a      ⇒      x := 10
y := x + 6             y := 16
t := x * y             t := x << 4
```

- Copy Propagation and Dead Code Elimination and Algebraic Simplification

```
x := z + y             x := z + y             x := z + y             x := z + y
a := x          ⇒      a := x         ⇒       x := 2 * x      ⇒      x := x + x
x := 2 * a             x := 2 * x
```

Assume (a is not used anywhere else)

Applying Local Optimizations

- Each local optimization does little by itself
- Typically optimizations interact, performing one optimization en
- Optimizing compilers repeat optimizations until no improvemen

a := x * x
~~b := 3~~
~~c := x~~
~~d := **a**~~
~~e := **6**~~
f := a + **a**
g := **6** * f

Dead code elimination

```
a := x ** 2
b := 3
c := x
d := c * c
e := b * 2
f := a + d
g := e * f
```

Algebraic optimization

```
a := x * x
b := 3
c := x
d := c * c
e := b << 1
f := a + d
g := e * f
```

Copy propagation

```
a := x * x
b := 3
c := x
d := x * x
e := 3 << 1
f := a + d
g := e * f
```

Constant folding

```
a := x * x
b := 3
c := x
d := x * x
e := 6
f := a + d
g := e * f
```

Common subexpression elimination

```
a := x * x
b := 3
c := x
d := a
e := 6
f := a + d
g := e * f
```

Copy propagation

```
a := x * x
b := 3
c := x
d := a
e := 6
f := a + a
g := 6 * f
```

Peephole Optimizations on Assembly Code

- These optimizations work on intermediate code
  - Target code
  - But they can be applied on IR
- Peephole optimization is effective for improving assembly code
  - The "peephole" is a short sequence of (usually contiguous) instructions
  - The optimizer replaces the sequence with another equivalent one (but faster

$$i_1, \ldots, i_n \rightarrow j_1, \ldots, j_m$$

Peephole Optimizations on Assembly Code

Eg. mov $a $b, mov $b $a → move $a $b

if move $b $a is not the target of a jump

- Flow-of-Control Optimizations

```
    goto L1

    …

L1: goto L2
```

$\Longrightarrow$

```
    goto L2

    …

L1: goto L2
```

- If there are no other jumps to `L1` and `L1` is preceded by an unconditional jump, the statement at `L1` can be eliminated
- Many of the basic block optimizations can be cast as peephole optimizations
- As for local optimizations, peephole optimizations must be applied repeatedly for maximum effect

Local Optimizations: Notes

- Intermediate code is helpful for many optimizations

- Many simple optimizations can still be applied on assembly language

- “Program optimization” is grossly misnamed
  - Code produced by “optimizers” is not optimal in any reasonable sense
  - “Program improvement” is a more appropriate term

Quiz

```
1       a := f * f + 0
2       b := a + 0
3       c := 2 + 8
4       d := c * b
5       e := f * f
6       x := e + d
7       g := b + d
8       h := b + d
9       i := g * 1
10      y := i / h
```

Assume that the only variables that are live at the exit of this block are x and y, while f is given as an input
In order, apply the following optimizations to this basic block.

(a) Algebraic simplification
(b) Copy propagation
(c) Common sub-expression elimination
(d) Constant folding
(e) Copy propagation
(f) Dead code elimination

Show the result of each transformation. For each optimization, you must continue to apply it until no further applications of that transformation are possible, before writing out the result and moving on to the next optimization

Optimizations

For languages like C and C++ there are three granularities of optimizations

Complexity

1. Local optimizations
    - Apply to a basic block in isolation
2. Global optimizations
    - Apply to a control-flow graph (method body) in isolation
3. Inter-procedural optimizations
    - Apply across method boundaries

powerful

Most compilers do (1), many do (2), few do (3)

Local vs. Global

- Local optimization involve statements within a single basic block
- All other optimizations are called global optimizations, e.g., peephole
- Local transformations are generally performed first
- Many types of transformations can be performed either locally or globally
- Global optimizations
  - ✓Data-flow analysis
  - ✓Intra-procedural analysis: across basic blocks, but not procedures
  - ✓Inter-procedural analysis: across procedures

Global Optimization

- Global optimizations
  1. Global common subexpressions
  2. Copy Propagation
  3. Dead-code Elimination
  4. Code motion
  5. Induction Variables and Reduction in Strength

Quicksort in C

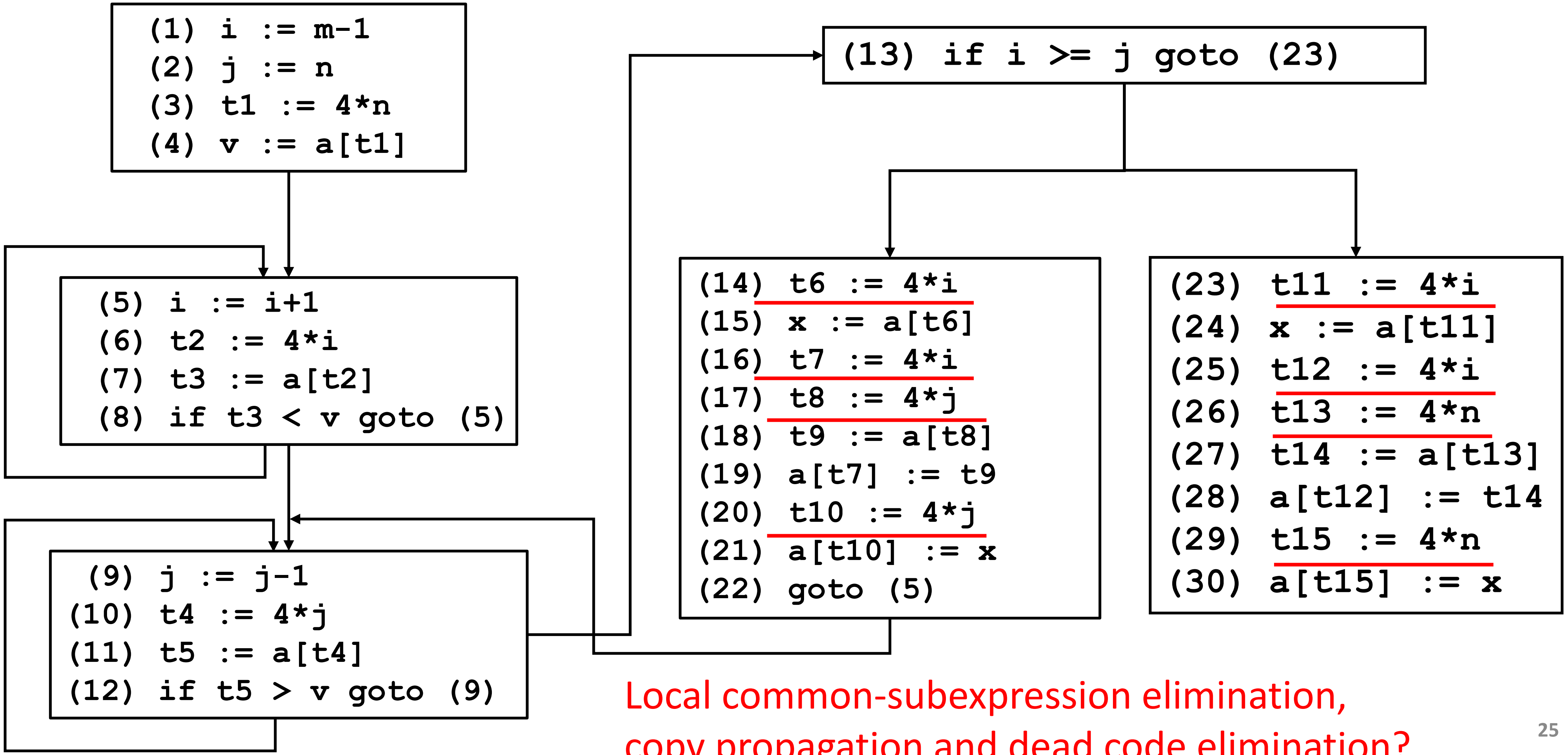
```
void quicksort(int m, int n) {
     int i, j, v, x;
     if (n <= m) return;
     /* Start of partition code */
     i = m-1; j = n; v =a[n];
     while (1) {
       do i = i+1; while (a[i] < v);
       do j = j-1; while (a[j] > v);
       if (i >= j) break;
       x = a[i]; a[i] = a[j]; a[j] = x;
     }
     x = a[i]; a[i] = a[n]; a[n] = x;
     /* End of partition code */
     quicksort(m, j); quicksort(i+1, n);
}
```

Partition in Three-Address Code

```
 (1)  i  := m-1
 (2)  j  := n
 (3)  t1  := 4*n
 (4)  v  := a[t1]
 (5)  i  := i+1
 (6)  t2  := 4*i
 (7)  t3  := a[t2]
 (8)  if t3 < v goto (5)
 (9)  j  := j-1
(10)  t4  := 4*j
(11)  t5  := a[t4]
(12)  if t5 > v goto (9)
(13)  if i >= j goto (23)
(14)  t6  := 4*i
(15)  x  := a[t6]
```

```
(16)  t7  := 4*i
(17)  t8  := 4*j
(18)  t9  := a[t8]
(19)  a[t7]  := t9
(20)  t10  := 4*j
(21)  a[t10]  := x
(22)  goto  (5)
(23)  t11  := 4*i
(24)  x  := a[t11]
(25)  t12  := 4*i
(26)  t13  := 4*n
(27)  t14  := a[t13]
(28)  a[t12]  := t14
(29)  t15  := 4*n
(30)  a[t15]  := x
```

Control-flow graph



```
(1) i := m-1
(2) j := n
(3) t1 := 4*n
(4) v := a[t1]
```

```
(5) i := i+1
(6) t2 := 4*i
(7) t3 := a[t2]
(8) if t3 < v goto (5)
```

```
 (9) j := j-1
(10) t4 := 4*j
(11) t5 := a[t4]
(12) if t5 > v goto (9)
```

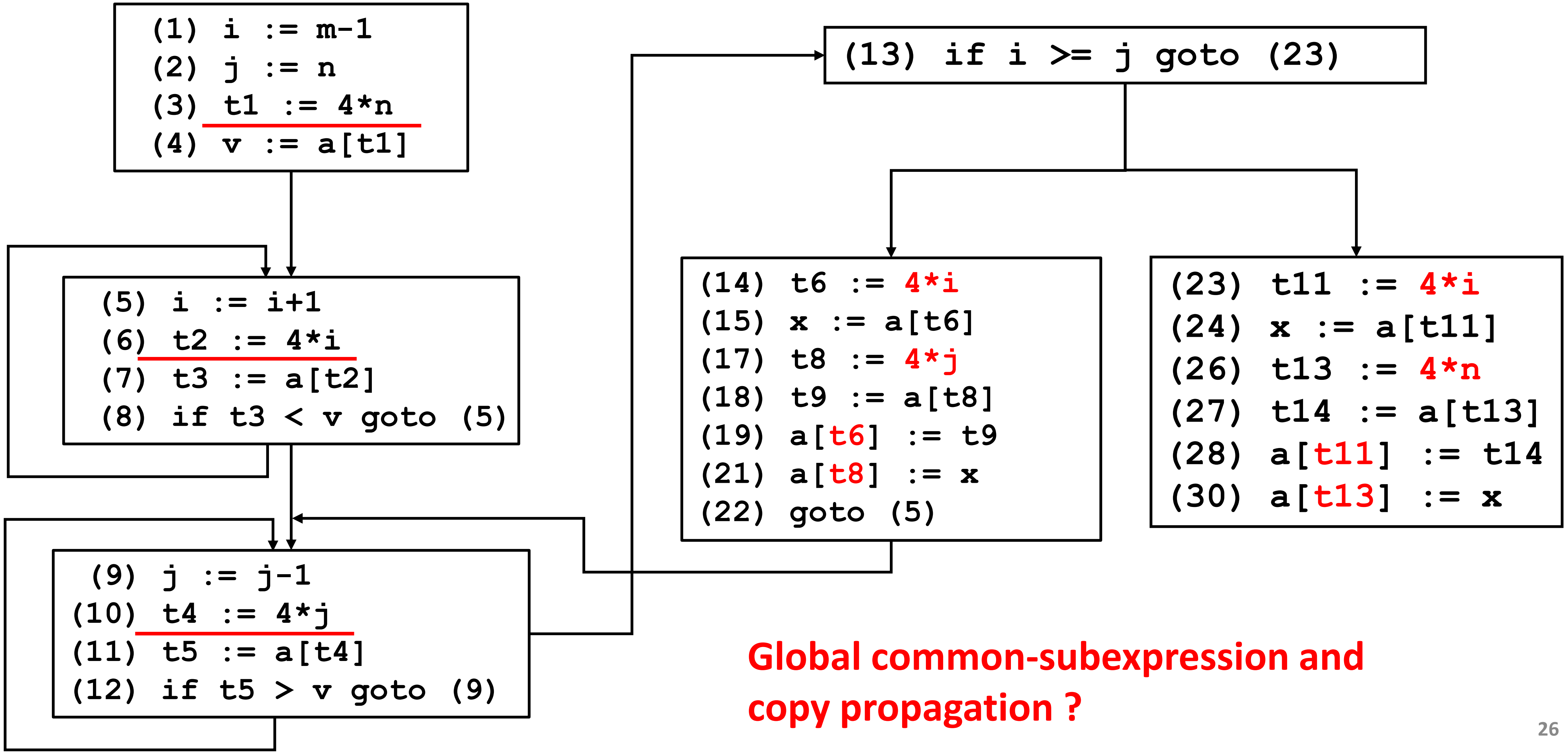
```
(13) if i >= j goto (23)
```

```
(14) t6 := 4*i
(15) x := a[t6]
(16) t7 := 4*i
(17) t8 := 4*j
(18) t9 := a[t8]
(19) a[t7] := t9
(20) t10 := 4*j
(21) a[t10] := x
(22) goto (5)
```

```
(23) t11 := 4*i
(24) x := a[t11]
(25) t12 := 4*i
(26) t13 := 4*n
(27) t14 := a[t13]
(28) a[t12] := t14
(29) t15 := 4*n
(30) a[t15] := x
```

Local common-subexpression elimination, copy propagation and dead code elimination?

Local common-subexpression elimination and dead code elimination



```
(1) i := m-1
(2) j := n
(3) t1 := 4*n
(4) v := a[t1]
```

```
(5) i := i+1
(6) t2 := 4*i
(7) t3 := a[t2]
(8) if t3 < v goto (5)
```

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 (9) j := j-1
(10) t4 := 4*j
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(12) if t5 > v goto (9)
```

```
(13) if i >= j goto (23)
```

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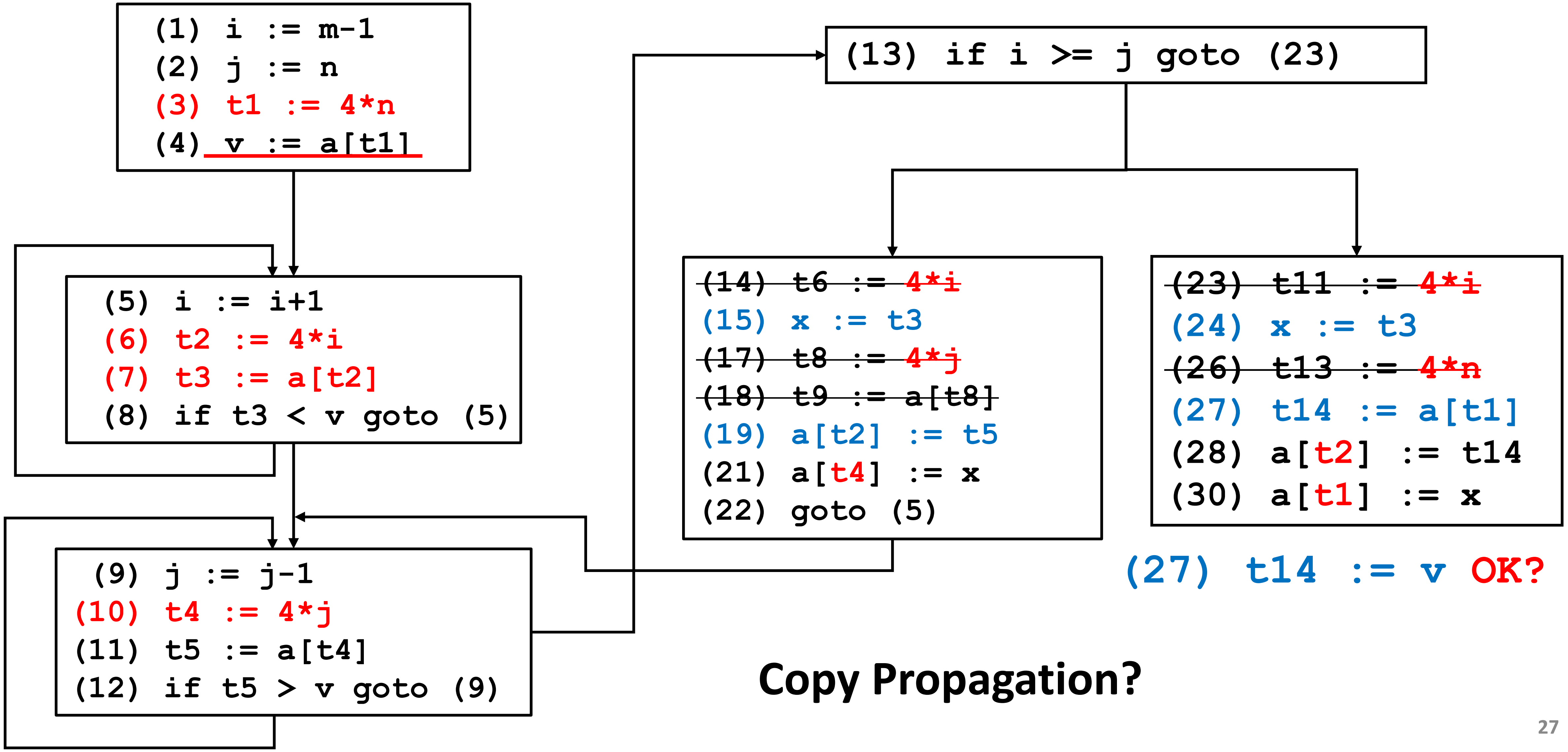
(18) t9 := a[t8]
(19) a[t6] := t9
(21) a[t8] := x
(22) goto (5)
```

```
(23) t11 := 4*i
(24) x := a[t11]
(26) t13 := 4*n
(27) t14 := a[t13]
(28) a[t11] := t14
(30) a[t13] := x
```

Global common-subexpression and copy propagation ?

Global common-subexpression



```
(1) i := m-1
(2) j := n
(3) t1 := 4*n
(4) v := a[t1]
```

```
(5) i := i+1
(6) t2 := 4*i
(7) t3 := a[t2]
(8) if t3 < v goto (5)
```

```
 (9) j := j-1
(10) t4 := 4*j
(11) t5 := a[t4]
(12) if t5 > v goto (9)
```

```
(13) if i >= j goto (23)
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```
~~(14) t6 := 4*i~~
(15) x := t3
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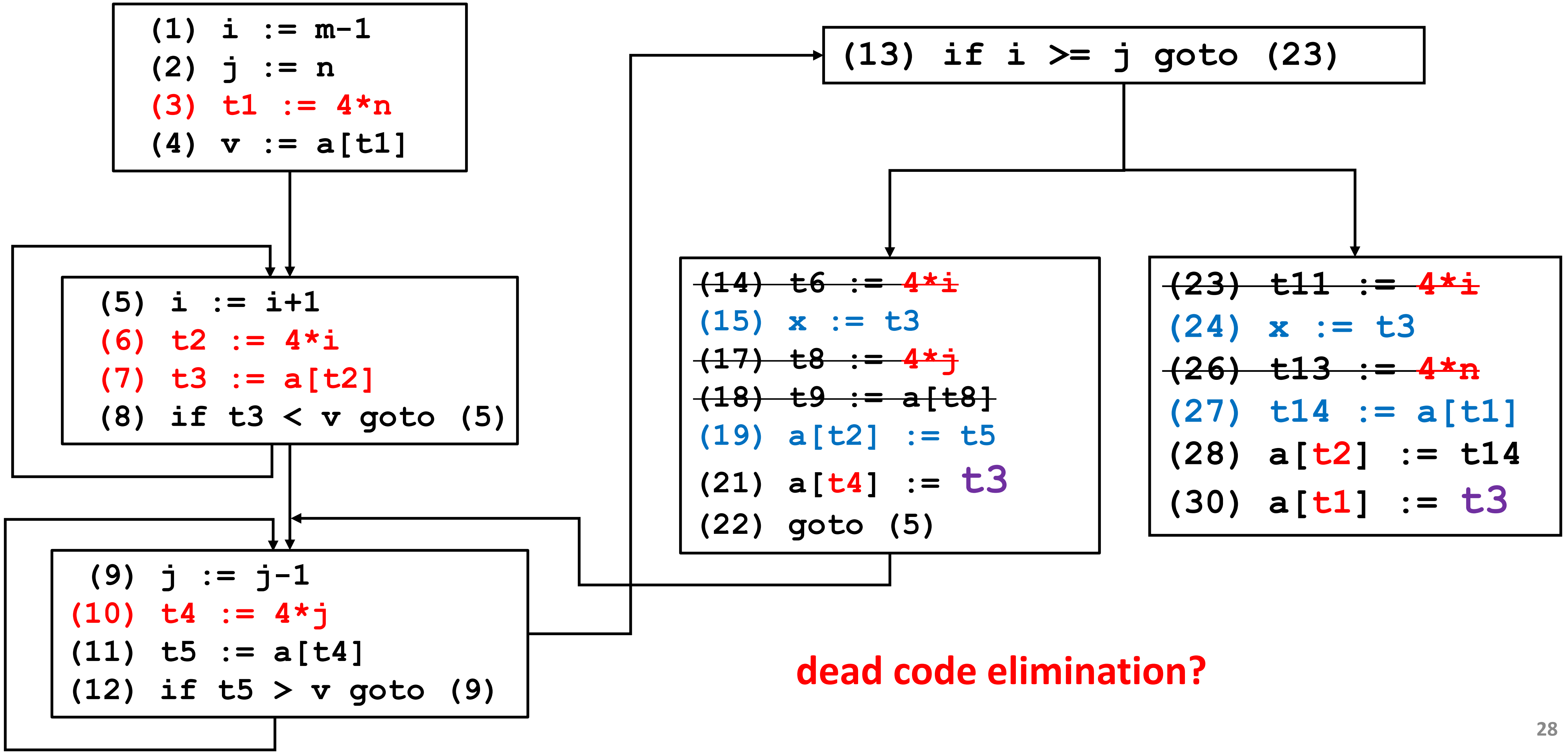
(19) a[t2] := t5
(21) a[t4] := x
(22) goto (5)
```

```
~~(23) t11 := 4*i~~
(24) x := t3
~~(26) t13 := 4*n~~
(27) t14 := a[t1]
(28) a[t2] := t14
(30) a[t1] := x
```

(27) t14 := v OK?

Copy Propagation?

Copy Propagation



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(7) t3 := a[t2]
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(19) a[t2] := t5
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(22) goto (5)

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(24) x := t3
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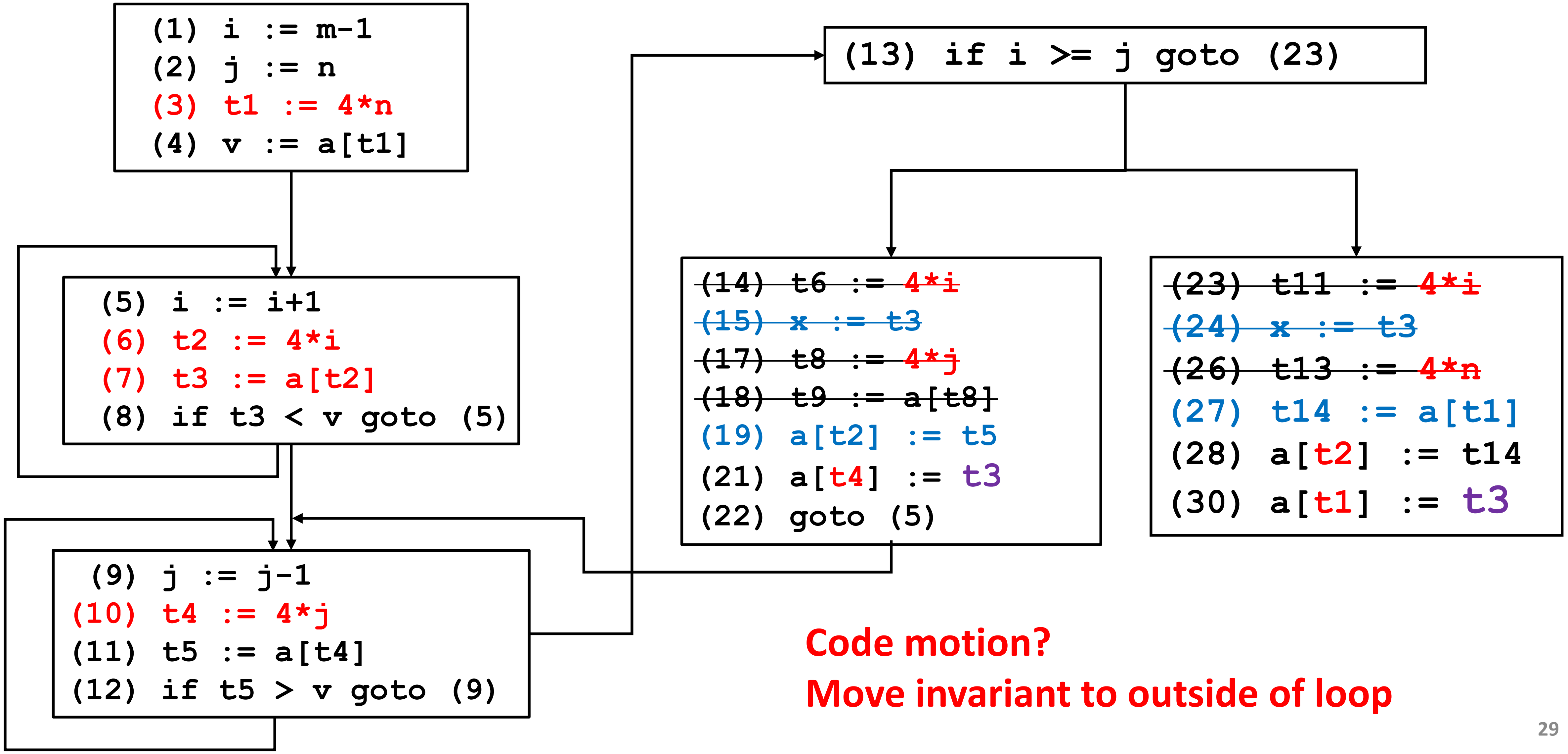
(27) t14 := a[t1]
(28) a[t2] := t14
(30) a[t1] := t3

dead code elimination?

Dead code elimination



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```

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(5) i := i+1
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(7) t3 := a[t2]
(8) if t3 < v goto (5)
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(9) j := j-1
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~~(24) x := t3~~
~~(26) t13 := 4*n~~
(27) t14 := a[t1]
(28) a[t2] := t14
(30) a[t1] := t3

Code motion?
Move invariant to outside of loop

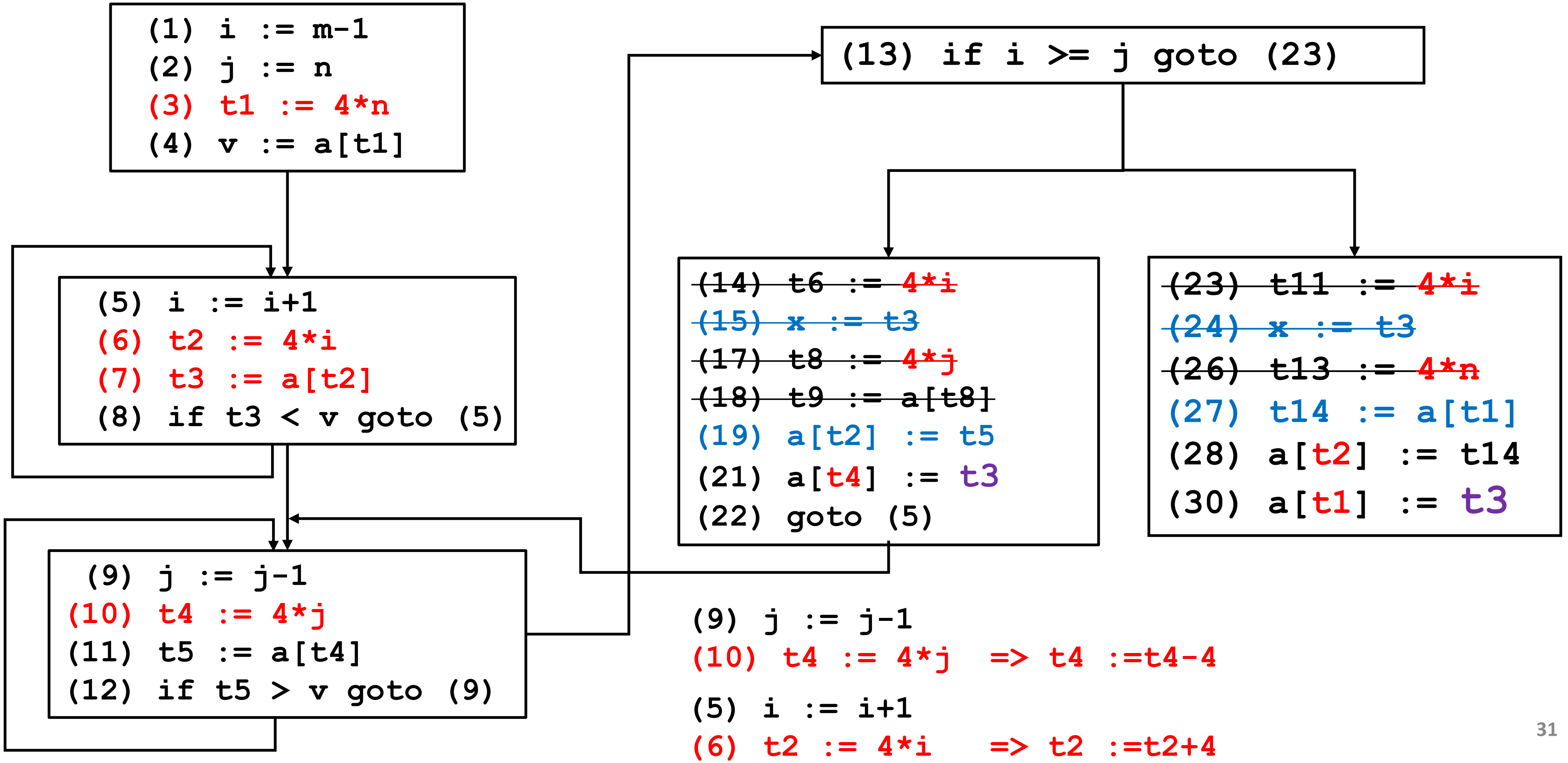
Code motion

Move invariant to outside of loop

```
While (i<= j-2) { … }  // j does not change in loop

=> t=j-2;  while (i<=t) {….}
```

Induction variables and Reduction in strength



```
(1) i := m-1
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(5) i := i+1
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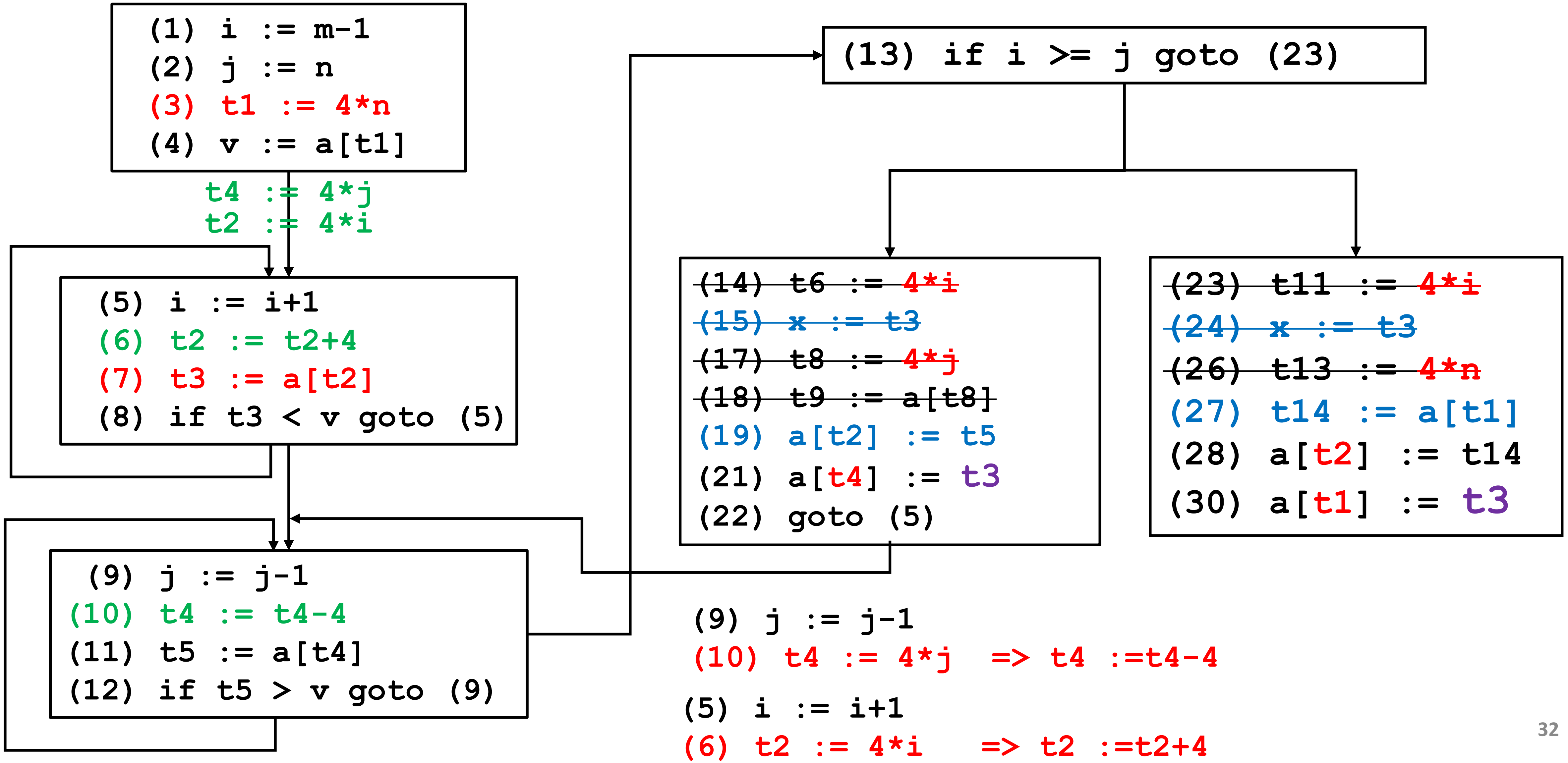
~~(26) t13 := 4*n~~
(27) t14 := a[t1]
(28) a[t2] := t14
(30) a[t1] := t3
```

```
(9) j := j-1
(10) t4 := 4*j   => t4 :=t4-4

(5) i := i+1
(6) t2 := 4*i    => t2 :=t2+4
```

Induction variables and Reduction in strength



```
(1) i := m-1
(2) j := n
(3) t1 := 4*n
(4) v := a[t1]
```

```
t4 := 4*j
t2 := 4*i
```

```
(5) i := i+1
(6) t2 := t2+4
(7) t3 := a[t2]
(8) if t3 < v goto (5)
```

```
 (9) j := j-1
(10) t4 := t4-4
(11) t5 := a[t4]
(12) if t5 > v goto (9)
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```
(13) if i >= j goto (23)
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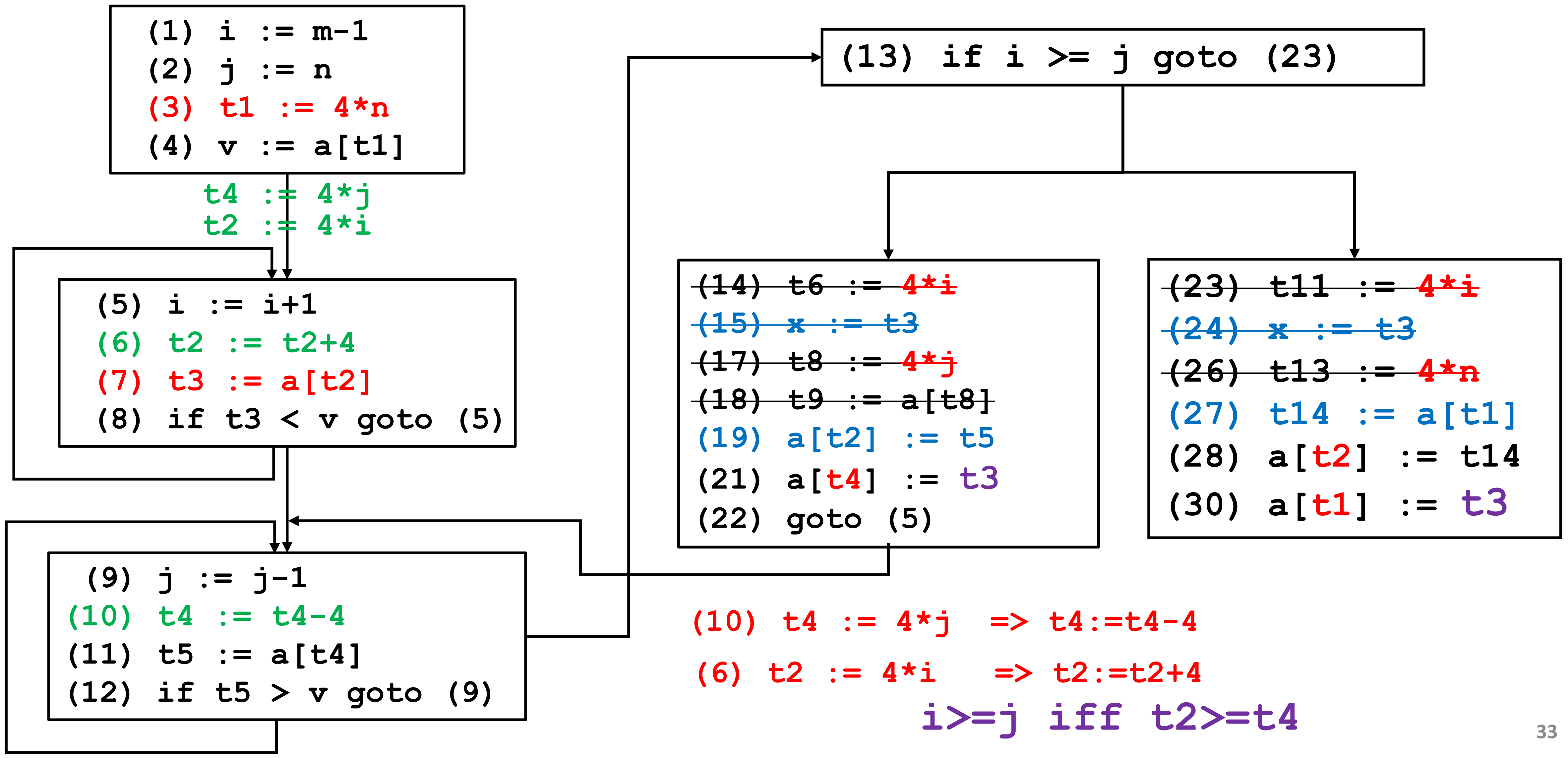
(30) a[t1] := t3
```

```
(9) j := j-1
(10) t4 := 4*j  => t4 :=t4-4

(5) i := i+1
(6) t2 := 4*i   => t2 :=t2+4
```

Induction variables and Reduction in strength



```
(1) i := m-1
(2) j := n
(3) t1 := 4*n
(4) v := a[t1]
```

```
t4 := 4*j
t2 := 4*i
```

```
(5) i := i+1
(6) t2 := t2+4
(7) t3 := a[t2]
(8) if t3 < v goto (5)
```

```
 (9) j := j-1
(10) t4 := t4-4
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(12) if t5 > v goto (9)
```

```
(13) if i >= j goto (23)
```

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```
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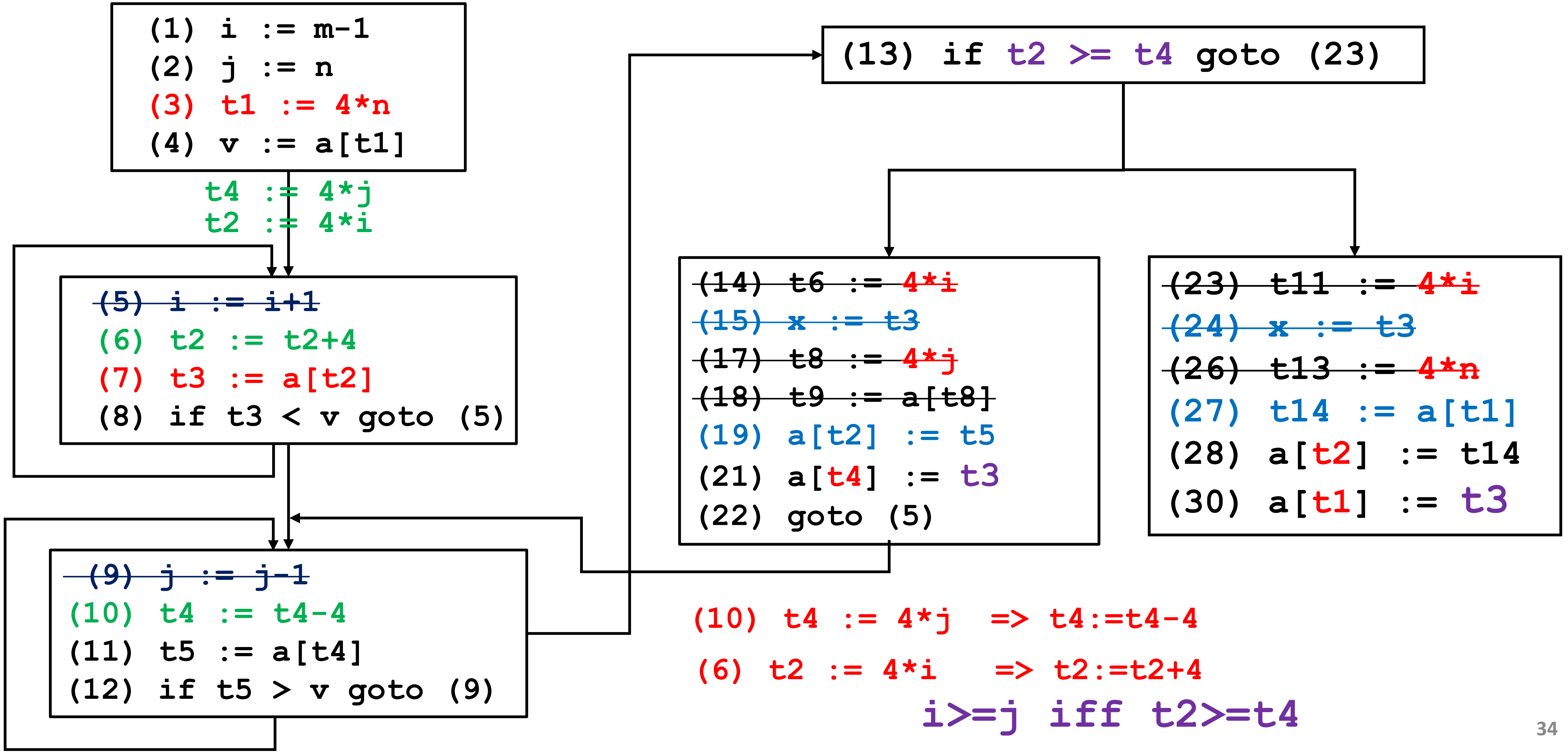
~~(26) t13 := 4*n~~
(27) t14 := a[t1]
(28) a[t2] := t14
(30) a[t1] := t3
```

```
(10) t4 := 4*j  => t4:=t4-4
(6)  t2 := 4*i   => t2:=t2+4
```

i>=j iff t2>=t4

Induction variables and Reduction in strength



(1) i := m-1
(2) j := n
(3) t1 := 4*n
(4) v := a[t1]

t4 := 4*j
t2 := 4*i

~~(5) i := i+1~~
(6) t2 := t2+4
(7) t3 := a[t2]
(8) if t3 < v goto (5)

~~(9) j := j-1~~
(10) t4 := t4-4
(11) t5 := a[t4]
(12) if t5 > v goto (9)

(13) if t2 >= t4 goto (23)

~~(14) t6 := 4*i~~
~~(15) x := t3~~
~~(17) t8 := 4*j~~
~~(18) t9 := a[t8]~~
(19) a[t2] := t5
(21) a[t4] := t3
(22) goto (5)

~~(23) t11 := 4*i~~
~~(24) x := t3~~
~~(26) t13 := 4*n~~
(27) t14 := a[t1]
(28) a[t2] := t14
(30) a[t1] := t3

(10) t4 := 4*j => t4:=t4-4

(6) t2 := 4*i => t2:=t2+4

i>=j iff t2>=t4