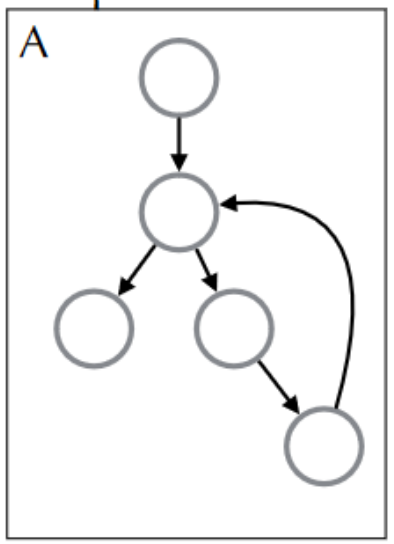
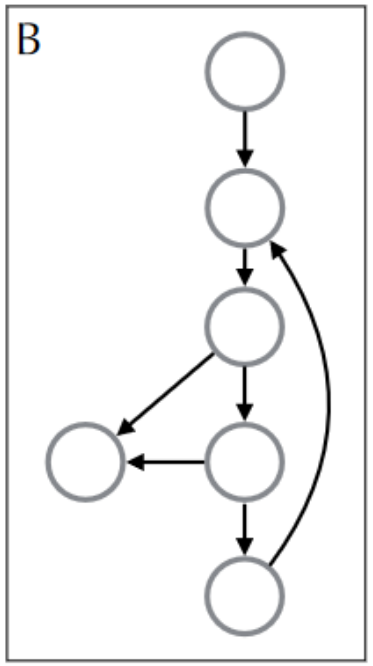
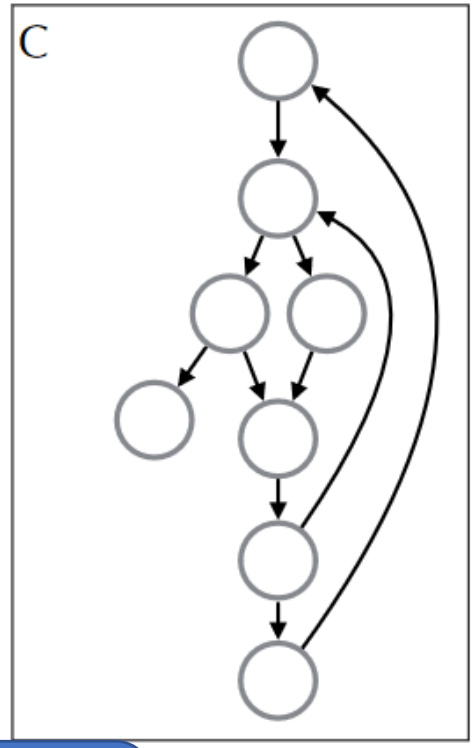
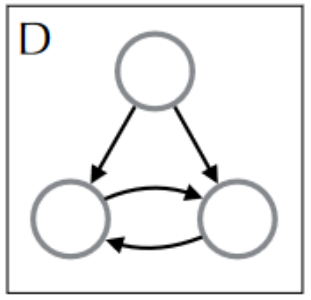
Pre-class Puzzle

- For each of these Control Flow Graphs (CFGs), what is a C program that corresponds to it?









Take some time to try to figure these out---I'll ask for volunteers to share their answers around 10:05

CS443: Compiler Construction

Lecture 15: Loop Optimization

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Based on material by Steve Zdancewic, Stephen Chong and Greg Morrisett

Announcements

- Project 4 due 10/20 (1 week from today)
  - Start early!
  - Partners may be helpful
- Project 3 will be graded next week
- OH Today
  - Online (obviously), usual Monday Zoom link
  - **3-4 pm** instead of 2-3pm

Loop optimizations are especially important!

- Programs spend most of the time in loops
- Lots of loop optimizations:
  - Loop invariant removal
  - Induction variable elimination
  - Loop unrolling
  - Loop fusion
  - Loop fission
  - Loop peeling
  - Loop interchange
  - Loop tiling
  - Loop parallelization
  - Software pipelining

Invariant removal: Don't recompute things in a loop

```
l0:
  %i = bitcast i32 0 to i32
  br %l1
l1:
  %i = add i32 %i 1
  %t = add i32 %a %b
  %el = getelementptr i32, i32* %arr, i32 %i
  store i32 %t, i32* %el
  %lt = icmp lt i32 %i %N
  br i1 %lt, label %l1, label %l2
l2:
  ret %t
```

Invariant removal: Don't recompute things in a loop

```
l0:
  %i = bitcast i32 0 to i32
  %t = add i32 %a %b
  br %l1
l1:
  %i = add i32 %i 1
  %el = getelementptr i32, i32* %arr, i32 %i
  store i32 %t, i32* %el
  %lt = icmp lt i32 %i %N
  br i1 %lt, label %l1, label %l2
l2:
  ret %t
```

Loop induction variable: Avoid recomputation based on loop induction variables

```
l0:
  %i = bitcast i32 0 to i32
l1:
  %t1 = mul i32 %i 4
  %t2 = add i32 %a %t1
  %s = add i32 %s %t2
  %i = add i32 %i 1
  %lt = icmp lt %i 100
  br i1 %lt, label %l1, label %l2
l2: …
```

t1 is always equal to i * 4

Loop induction variable: Avoid recomputation based on loop induction variables

```
l0:
  %i = bitcast i32 0 to i32
  %t1 = bitcast i32 0 to i32
l1:
  %t1 = add i32 %t1 4
  %t2 = add i32 %a %t1
  %s = add i32 %s %t2
  %i = add i32 %i 1
  %lt = icmp lt %i 100
  br i1 %lt, label %l1, label %l2
l2: …
```

t2 is always a + i * 4

Loop induction variable: Avoid recomputation based on loop induction variables

```
l0:
  %i = bitcast i32 0 to i32
  %t1 = bitcast i32 0 to i32
  %t2 = bitcast i32 %a to i32
l1:
  %t1 = add i32 %t1 4
  %t2 = add i32 %t2 %4
  %s = add i32 %s %t2
  %i = add i32 %i 1
  %lt = icmp lt %i 100
  br i1 %lt, label %l1, label %l2
l2: …
```

Can eliminate t1!

Loop induction variable: Avoid recomputation based on loop induction variables

```
l0:
  %i = bitcast i32 0 to i32
  %t2 = bitcast i32 %a to i32
l1:  %t2 = add i32 %t2 %4
  %s = add i32 %s %t2
  %i = add i32 %i 1
  %lt = icmp lt %i 100
  br i1 %lt, label %l1, label %l2
l2: …
```

Can eliminate i!

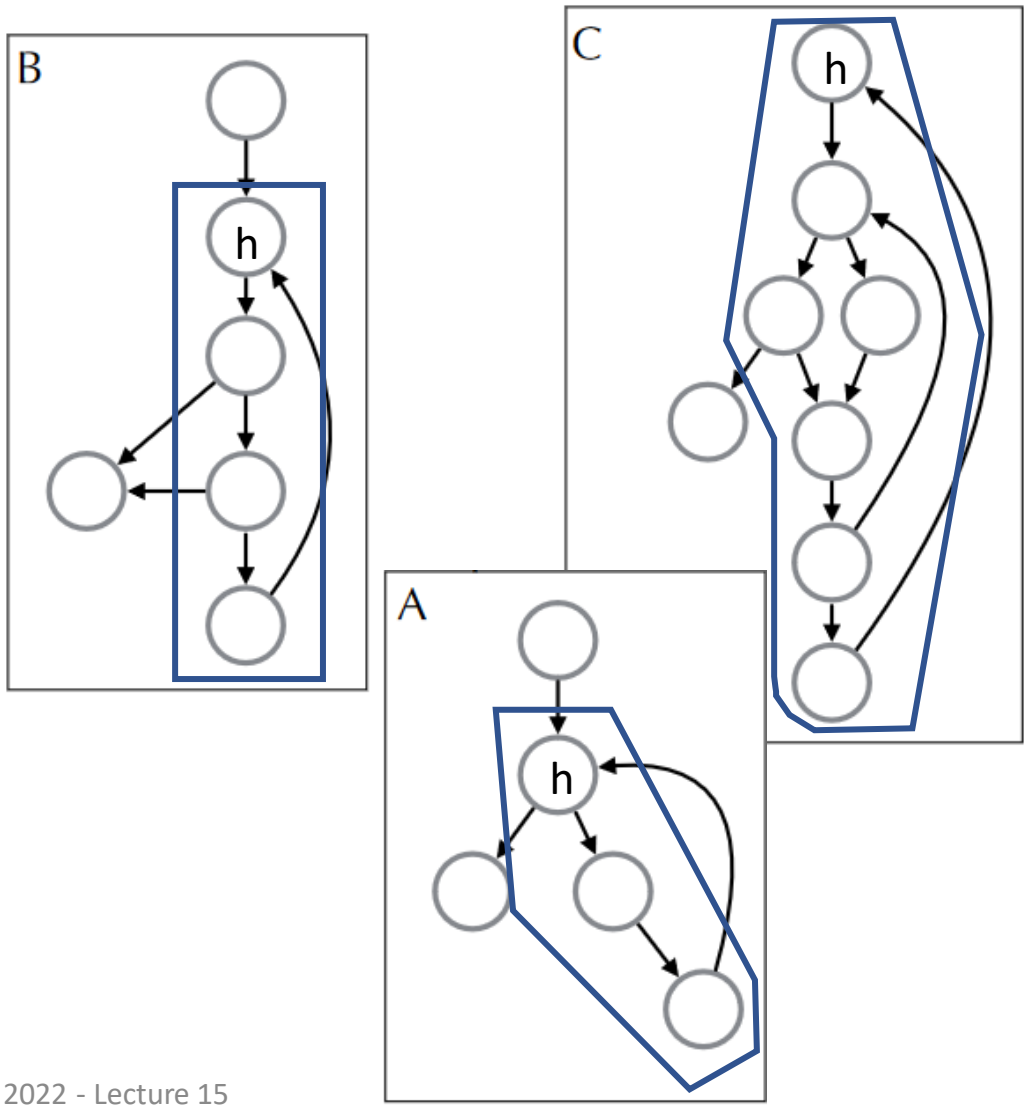
Loop induction variable: Avoid recomputation based on loop induction variables

```
l0:
  %i = bitcast i32 0 to i32
  %t2 = bitcast i32 %a to i32
  %endt2 = add i32 %a 400
l1:
  %t2 = add i32 %t2 %4
  %s = add i32 %s %t2
  %lt = icmp lt %t2 %endt2
  br i1 %lt, label %l1, label %l2
l2: …
```

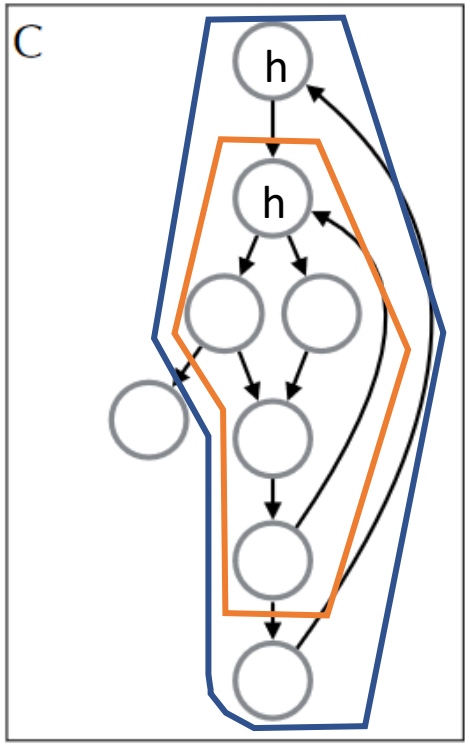
Before we can optimize loops, we have to find them

- In C: easy!
- In LLVM: surprisingly hard!

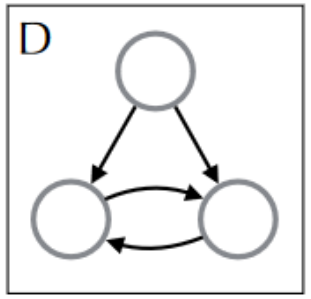
- **Definition** (loop):
  - Subset S of nodes in CFG
  - Designated “header” node h
  - S is strongly connected
  - No edge from outside S to S \ {h}



Loops can be nested

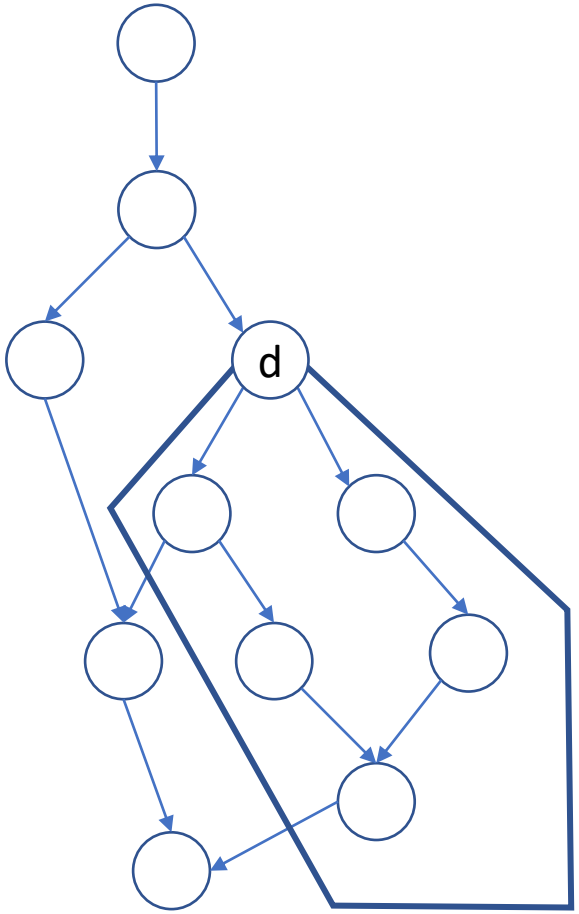


Non-example: (there can’t be a header)



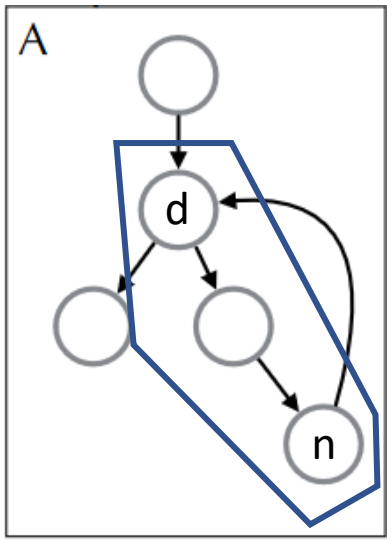
- (But this can’t arise in C/C++ without goto)

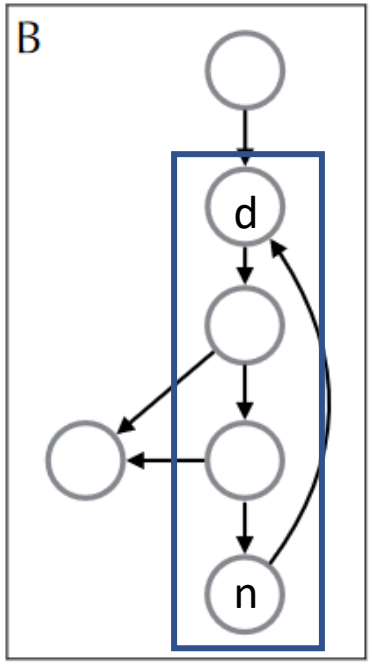
A node *d dominates n* if every path (from start) to *n* must go through *d*

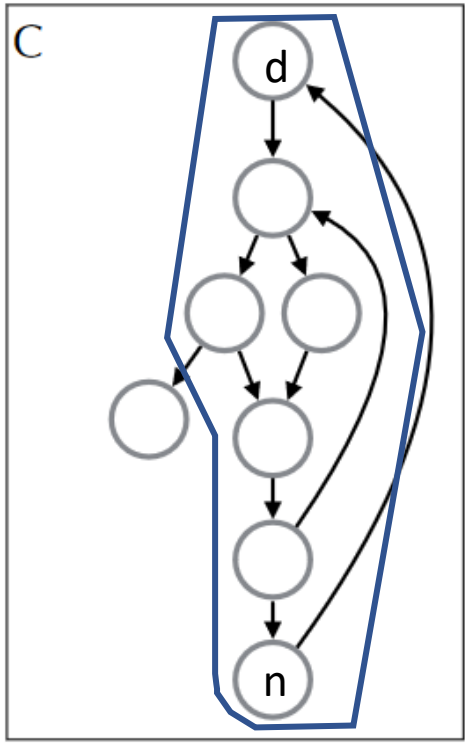


We can define loops based on dominators

- A **back edge** is an edge from *n* to a dominator *d*
- If there's a back edge n -> d, there is a **loop** consisting of the set of nodes *x* such that *d* dominates *x* and there is a path from *x* to *n* not including *d*

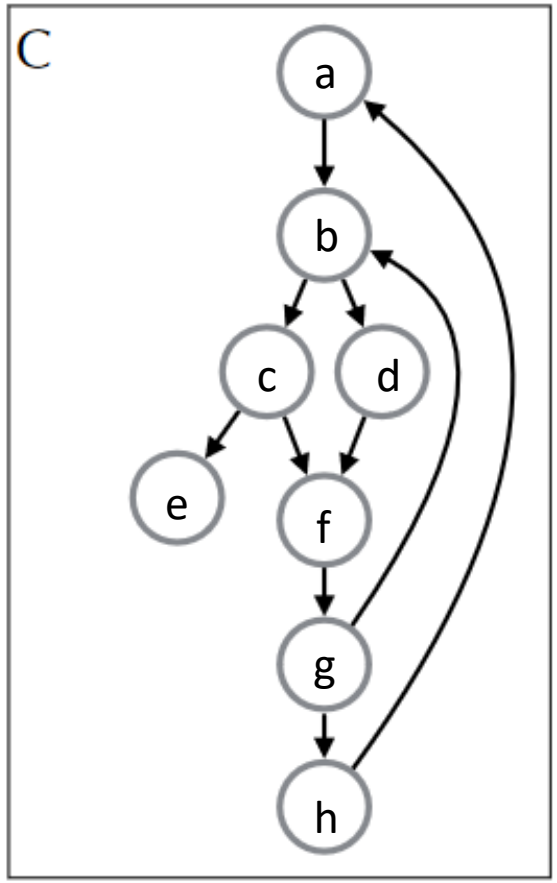






Example

- For each node, what nodes does it dominate? Back edges?
- a dominates a, b, c, d, e, f, g, h
- b dominates b, c, d, e, f, g, h
- c dominates c, e
- d dominates d
- f dominates f, g, h
- g dominates g, h
- h dominates h,
- Back edges: g -> b, h -> a

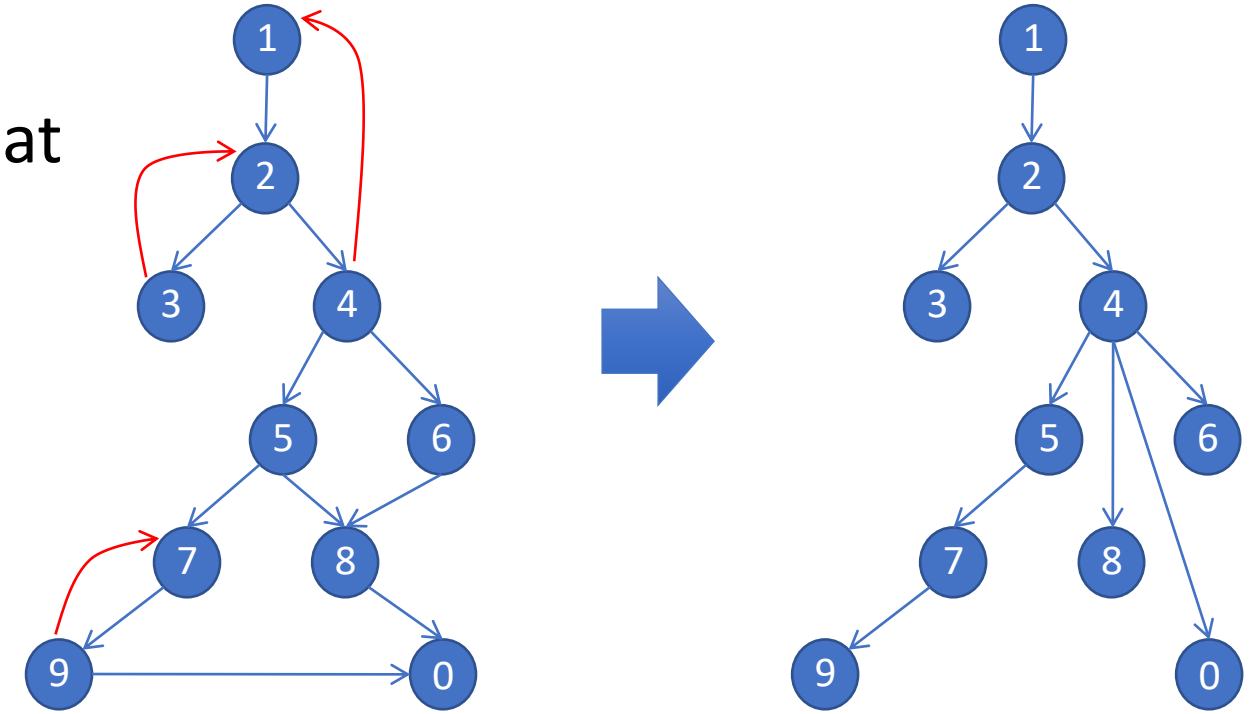


We can calculate dominators with a dataflow analysis!

- out[n] = set of nodes that dominate n
  - in[n] := $\cap_{n' \in pred[n]} out[n']$
  - out[n] := in[n] $\cup$ {n}
- Forward must analysis: initialize out[n], in[n] to all nodes

We can represent dominators with a "dominator tree"

- Edge to n from its "immediate dominator" (dominator other than n that is dominated by other dominators other than n)



Identifying loop invariants

- An instruction `%x = opc op1, op2, …, opN` represented by a node *n* is invariant for a loop if for each operand op*i*:
  - op*i* is constant, or
  - all definitions of op*i* that reach *n* are outside the loop, or
  - only one definition reaches op*i* and it is a loop invariant

Loop invariant example from before

```
l0:
  %i = bitcast i32 0 to i32
  br %l1
l1:
  %i = add i32 %i 1
  %t = add i32 %a %b
  %el = getelementptr i32, i32* %arr, i32 %i
  store i32 %t, i32* %el
  %lt = icmp lt i32 %i %N
  br i1 %lt, label %l1, label %l2
l2:
  ret %t
```

Actually moving (*hoisting*) invariants out of the loop is pretty tricky

- Move to a “pre-header” (CFG node before header)

Need to make sure hoisting wouldn't interfere with other uses!

```
l0:
  %i = bitcast i32 0 to i32
  br %l1
l1:
  %i = add i32 %i 1
  %el = getelementptr i32, i32* %arr, i32 %i
  store i32 %t, i32* %el
  %t = add i32 %a %b
  %lt = icmp lt i32 %i %N
  br i1 %lt, label %l1, label %l2
l2:
  ret %t
```

Need to make sure hoisting wouldn't interfere with other uses!

- n := `%x = opc op1, op2, …, opN` is safe to hoist if:
  - *n* dominates all loop exits at which *%x* is live, and
  - there is only one definition of *x* in the loop, and
  - *x* is not live at the pre-header

```
for (i = 0; i < 100; i += 2) {
  t = a + b;
  a[i] = t;
  t = a – b;
  a[i + 1] = t;
}
```

```
t = 0;
while(1) {
  break;
  t = a + b;
  a[i] = t;
}
return t;
```

Loop Unrolling: Copy over the body of a loop

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

```
//Handle the first few in case n not a multiple of 3
for (int i = 0; i < n % 3; ++i) a[i] = i;
for (; i < n; i+=3) {
  a[i] = i;
  a[i + 1] = i + 1;
  a[i + 2] = i + 2;
}
```

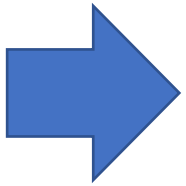
Why is this an optimization?

Loop unrolling: costs and benefits

- Benefits:
  - Amortize tests, jumps over more instructions
- Costs:
  - Program size increases (why is this a problem?)

Loop Peeling: "Peel off" the first or last N iterations of a loop

```
for (int i = 0; i < N; i++) {
  if (i <= 1) {
    a[i] = i;
  } else {
    a[i] = a[i – 1] + a[i – 2];
  }
}
```



```
a[0] = 0;
a[1] = 1;
for (int i = 2; i < N; i++) {
  a[i] = a[i – 1] + a[i – 2];
}
```

Loop Interchange: Swap order of nested loops

```
for (int i = 0; i < w; i++) {
  for (int j = 0; j < h; j++) {
    sum += a[j][i];
  }
}
```

```
for (int j = 0; j < h; j++) {
  for (int i = 0; i < w; i++) {
    sum += a[j][i];
  }
}
```

Why is this an optimization?