CSE110A: Compilers

June 2, 2023

Topics:

- *Finish local value numbering*
- *Loop transformations*

Announcements

- HW 5 is out
  - Get started early
  - I don’t expect you to work over the weekend, but I am giving you the time
- Grading
  - HW 2 grades are out, let us know if there are any issues
  - HW 3 grades should be coming soon
- Final:
  - June 12th at 8 AM
  - Like the midterm, but with 4 questions (comprehensive)
  - 3 pages of notes

Announcements

- Next Wednesday, guest lecture by teaching staff
  - Neal will talk about register allocation
  - Rithik will talk about LLVM

- Not enough time to cover many optimizations or backends ☹
  - Book is a good reference
  - CSE 211 will go over more types of analysis. Message me if you are interested

No quiz

- Thanks for filling out SETs!

Finishing up local value numbering

- How to stitch optimized code back into the whole program

How to stitch optimized code back into the program

```
a = b + c;
d = e + f;
g = b + c;

label_0:
h = g + a;
k = a + g;
```

How to stitch optimized code back into the program

split into basic blocks

```
a = b + c;
d = e + f;
g = b + c;

label_0:
h = g + a;
k = a + g;
```

```
a = b + c;
d = e + f;
g = b + c;
```

```
label_0:
h = g + a;
k = a + g;
```

How to stitch optimized code back into the program

number

```
a = b + c;
d = e + f;
g = b + c;

label_0:
h = g + a;
k = a + g;
```

```
a = b + c;
d = e + f;
g = b + c;

label_0:
h = g + a;
k = a + g;
```

```
a2 = b0 + c1;
d5 = e3 + f4;
g6 = b0 + c1;

label_0:
h2 = g0 + a1;
k3 = a1 + g0;
```

How to stitch optimized code back into the program

move code on slide to make room

```
a2 = b0 + c1;
d5 = e3 + f4;
g6 = b0 + c1;
```

```
label_0:
h2 = g0 + a1;
k3 = a1 + g0;
```

How to stitch optimized code back into the program

optimize

```
a2 = b0 + c1;
d5 = e3 + f4;
g6 = b0 + c1;
```

```
a2 = b0 + c1;
d5 = e3 + f4;
g6 = a2;
```

```
label_0:
h2 = g0 + a1;
k3 = a1 + g0;
```

```
label_0:
h2 = g0 + a1;
k3 = h2;
```

How to stitch optimized code back into the program

optimize

put together?

```
a2 = b0 + c1;
d5 = e3 + f4;
g6 = b0 + c1;
```

```
label_0:
h2 = g0 + a1;
k3 = a1 + g0;
```

```
a2 = b0 + c1;
d5 = e3 + f4;
g6 = a2;
```

```
label_0:
h2 = g0 + a1;
k3 = h2;
```

```
a2 = b0 + c1;
d5 = e3 + f4;
g6 = a2;
label_0:
h2 = g0 + a1;
k3 = h2;
```

How to stitch optimized code back into the program

original code

```
a = b + c;
d = e + f;
g = b + c;

label_0:
h = g + a;
k = a + g;
```

put together?

```
a2 = b0 + c1;
d5 = e3 + f4;
g6 = a2;
label_0:
h2 = g0 + a1;
k3 = h2;
```

What are the issues?

How to stitch optimized code back into the program

original code

```
a = b + c;
d = e + f;
g = b + c;

label_0:
h = g + a;
k = a + g;
```

put together?

```
a2 = b0 + c1;
d5 = e3 + f4;
g6 = a2;
label_0:
h2 = g0 + a1;
k3 = h2;
```

undefined!

What are the issues?

How to stitch optimized code back into the program

stitch
part 1: *assign original variables their latest values*

```
a = b + c;
d = e + f;
g = b + c;

label_0:
h = g + a;
k = a + g;
```

```
a2 = b0 + c1;
d5 = e3 + f4;
g6 = a2;
g = g6;
d = d5
a = a2;
```

```
label_0:
h2 = g0 + a1;
k3 = h2;
h = h2;
k = k3;
```

How to stitch optimized code back into the program

make room on slide

```
a2 = b0 + c1;
d5 = e3 + f4;
g6 = a2;
g = g6;
d = d5
a = a2;
```

```
label_0:
h2 = g0 + a1;
k3 = h2;
h = h2;
k = k3;
```

what else needs to be done?

How to stitch optimized code back into the program

stitch part 2: drop numbers from first use of variables

```
a2 = b0 + c1;
d5 = e3 + f4;
g6 = a2;
g = g6;
d = d5
a = a2;
```

```
a2 = b + c;
d5 = e + f;
g6 = a2;
g = g6;
d = d5
a = a2;
```

```
label_0:
h2 = g0 + a1;
k3 = h2;
h = h2;
k = k3;
```

```
label_0:
h2 = g + a;
k3 = h2;
h = h2;
k = k3;
```

How to stitch optimized code back into the program

```
a2 = b0 + c1;
d5 = e3 + f4;
g6 = a2;
g = g6;
d = d5
a = a2;
```

```
label_0:
h2 = g0 + a1;
k3 = h2;
h = h2;
k = k3;
```

Now they can be combined

```
a2 = b + c;
d5 = e + f;
g6 = a2;
g = g6;
d = d5
a = a2;
```

```
label_0:
h2 = g + a;
k3 = h2;
h = h2;
k = k3;
```

```
a2 = b + c;
d5 = e + f;
g6 = a2;
g = g6;
d = d5
a = a2;
label_0:
h2 = g + a;
k3 = h2;
h = h2;
k = k3;
```

How to stitch optimized code back into the program

original

```
a = b + c;
d = e + f;
g = b + c;

label_0:
h = g + a;
k = a + g;
```

new

```
a2 = b + c;
d5 = e + f;
g6 = a2;
g = g6;
d = d5
a = a2;
label_0:
h2 = g + a;
k3 = h2;
h = h2;
k = k3;
```

is it really optimized?

It looks a lot longer...

How to stitch optimized code back into the program

original

```
a = b + c;
d = e + f;
g = b + c;

label_0:
h = g + a;
k = a + g;
```

new

```
a2 = b + c;
d5 = e + f;
g6 = a2;
g = g6;
d = d5
a = a2;
label_0:
h2 = g + a;
k3 = h2;
h = h2;
k = k3;
```

is it really optimized?

Common pattern for code to get larger, but it will contain patterns that are easier optimize away

later passes will minimize copies

New material

- Loop transformations

Loop optimizations

- Regional optimization
  - We can handle multiple basic blocks
  - but only if they fit a certain pattern

For loops

- How do they look in different languages
  - C/C++
  - Python
  - Numpy

- The more constrained the for loops are, the more assumptions the compiler can make, but less flexibility for the programmer

For loops

- The compiler can optimize For loops if they fit a certain pattern

- When developing a regional optimization, we start with strict constraints and then slowly relax them and make the optimization more general.
  - Sometimes it is not worth relaxing the constraints (optimization gets too complicated. Its not the compilers job to catch every pattern!)
  - If a programmer knows the pattern, then often you can write code such that the compiler can recognize the pattern and it will do better at optimizing!
  - Thus you can write more efficient code if you write it in such a way that the compiler can recognize patterns

For loops terminology

- Loop body:
  - A series of statements that are executed each loop iteration
- Loop condition:
  - the condition that decides whether the loop body is executed
- Iteration variable:
  - A variable that is updated exactly once during the loop
  - The loop condition depends on the iteration variable
  - The loop condition is only updated through the iteration variable

Examples

iteration variable
loop body
loop condition

```
for (int i = 0; i < 1024; i++) {
    counter += 1;
  }
```

```
for (; i < 1024; i+=counter) {
    counter += 1;
  }
```

```
  while (1) {
    i++;
    counter += 1;
    if (i < 1024) {
      break;
    }
  }
```

In general, is it possible to determine if an iteration variable exists or not?

Examples

What about these?

```
for (i = 0; i < 1024; i++) {
    counter += 1;
    foo();
  }
```

```
for (i = 0; i < j; i++) {
    counter += 1;
    j = rand();
  }
```

Loop unrolling

Loop unrolling

- Executing multiple instances of the loop body without checking the loop condition.

```
FOR LPAR assignment_statement expr SEMI assignment_statement RPAR statement
```

unrolled by a **factor** of 2

```
for (int i = 0; i < 128; i++) {
   // body
}
```

```
for (int i = 0; i < 128; i++) {
   // body
   i++
   // body
}
```

could we unroll more?

Loop unrolling conditions

- Under what conditions can we unroll?

```
FOR LPAR assignment_statement expr SEMI assignment_statement RPAR statement
```

```
for (int i = 0; i < 128; i++) {
   // body
}
```

```
for (int i = 0; i < 128; i++) {
   // body
   i++
   // body
}
```

What can go wrong?

Loop unrolling conditions

- Under what conditions can we unroll?

FOR LPAR assignment_statement expr SEMI assignment_statement RPAR statement

```
for (int i = 0; i < 128; i++) {
  // body
}
```

Validate that we actually have an iteration variable

Loop unrolling conditions

- Under what conditions can we unroll?

FOR LPAR assignment_statement expr SEMI assignment_statement RPAR statement

```
for (int i = 0; i < 128; i++) {
  // body
}
```

Validate that we actually have an iteration variable

1. **find** candidate on lhs of assignment statement

Loop unrolling conditions

- Under what conditions can we unroll?

```
FOR LPAR assignment_statement expr SEMI assignment_statement RPAR statement
```

```
for (int i = 0; i < 128; i++) {
  // body
}
```

Validate that we actually have an iteration variable

1. **find** candidate on lhs of assignment statement
2. **check** no assignments to candidate in body

Loop unrolling conditions

- Under what conditions can we unroll?

```
FOR LPAR assignment_statement expr SEMI assignment_statement RPAR statement
```

```
for (int i = 0; i < 128; i++) {
  // body
}
```

Validate that we actually have an iteration variable

1. **find** candidate on lhs of assignment statement
2. **check** no assignments to candidate in body
3. **check** that it matches lhs of assignment_statement

Loop unrolling conditions

- Under what conditions can we unroll?

```
FOR LPAR assignment_statement expr SEMI assignment_statement RPAR statement
```

```
for (int i = 0; i < 128; i++) {
  // body
}
```

Validate that we actually have an iteration variable

1. **find** candidate on lhs of assignment statement
2. **check** no assignments to candidate in body
3. **check** that it matches lhs of assignment_statement
4. **check** loop condition
   * check that candidate variable is on lhs
   * check that the rhs is a literal

Loop unrolling conditions

- Under what conditions can we unroll?

```
FOR LPAR assignment_statement expr SEMI assignment_statement RPAR statement
```

```
for (int i = 0; i < 128; i++) {
  // body
}
```

Validate that we actually have an iteration variable

1. **find** candidate on lhs of assignment statement
2. **check** no assignments to candidate in body
3. **check** that it matches lhs of assignment_statement
4. **check** loop condition
   * check that candidate variable is on lhs
   * check that the rhs is a literal

Do these guarantee we will find an iteration variable?
What happens if we don't find one?

Loop unrolling conditions

- Several ways to unroll
  - More constraints: Simpler to unroll in code generation
  - Less constraints: Harder to unroll in code generation

Base constraints (required for any unrolling):

Validate that we actually have an iteration variable

1. **find** candidate on lhs of assignment statement
2. **check** no assignments to candidate in body
3. **check** that it matches lhs of assignment_statement
4. **check** loop condition
   * check that candidate variable is on lhs
   * check that the rhs is a literal

Loop unrolling conditions

- Simple unroll
  - Most constraints
  - Easiest code generation

For unroll factor F

Simple unroll constraints:

- Loop update increments by 1
- Find the concrete number of loop iterations, LI
- F must divide LI evenly

Simple unroll code generation:

- create a new body = body + update + body
- perform codegen

Loop unrolling conditions

FOR LPAR assignment_statement expr SEMI assignment_statement RPAR statement

```
for (int i = 0; i < 128; i++) {
  // body
}
```

how to do these steps?

For unroll factor F

Simple unroll constraints:

- Loop update increments by 1
- Find the concrete number of loop iterations, LI
- F must divide LI evenly

Simple unroll code generation:

- create a new body = body + update + body
- perform codegen

Loop unrolling conditions

FOR LPAR assignment_statement expr SEMI assignment_statement RPAR statement

```
for (int i = 0; i < 128; i++) {
   // body
}
```

result for a factor of 2

```
for (int i = 0; i < 128; i++) {
   // body
   i++
   // body
}
```

For unroll factor F

Simple unroll constraints:

- Loop update increments by 1
- Find the concrete number of loop iterations, LI
- F must divide LI evenly

Simple unroll code generation:

- create a new body = body + update + body
- perform codegen

Loop unrolling conditions

what can go wrong?

FOR LPAR assignment_statement expr SEMI assignment_statement RPAR statement

```
for (int i = 0; i < 8; i+=3) {
  // body
}
```

For unroll factor F

Simple unroll constraints:

- Loop update increments by 1
- Find the concrete number of loop iterations, LI
- F must divide LI evenly

Simple unroll code generation:

- create a new body = body + update + body
- perform codegen

Loop unrolling conditions

what can go wrong?

```
FOR LPAR assignment_statement expr SEMI assignment_statement RPAR statement
```

```
for (int i = 0; i < 8; i+=3) {
  // body
}
```

Actually this is fine as long as i is updated with a constant addition. but we need a more complicated formula to calculate LI:

```
ceil((end - start)/update)
```

But you may want to keep your life simpler by constraining it. We will keep it for now

For unroll factor F

Simple unroll constraints:

- Loop update increments by 1
- Find the concrete number of loop iterations, LI
- F must divide LI evenly

Simple unroll code generation:

- create a new body = body + update + body
- perform codegen

Loop unrolling conditions

what can go wrong?

```
FOR LPAR assignment_statement expr SEMI assignment_statement RPAR statement
```

```
for (int i = 0; i < 4; i++) {
  // body
}
```

What if we try to unroll this by a factor of 3?

For unroll factor F

Simple unroll constraints:

- Loop update increments by 1
- Find the concrete number of loop iterations, LI
- F must divide LI evenly

Simple unroll code generation:

- create a new body = body + update + body
- perform codegen

Loop unrolling conditions

what can go wrong?

```
FOR LPAR assignment_statement expr SEMI assignment_statement RPAR statement
```

```
for (int i = 0; i < 4; i++) {
  // body
}
```

```
for (int i = 0; i < 4; i++) {
  // body
  i++
  // body
  i++
  // body
}
```

What if we try to unroll this by a factor of 3?

How many times do we execute body?

For unroll factor F

Simple unroll constraints:

- Loop update increments by 1
- Find the concrete number of loop iterations, LI
- F must divide LI evenly

Simple unroll code generation:

- create a new body = body + update + body
- perform codegen

Loop unrolling conditions

Let's examine this a bit closer?

```
for (int i = 0; i < 4; i++) {
   // body
}
```

What if we try to unroll this by a factor of 3?

```
for (int i = 0; i < 4; i++) {
   // body
   i++
   // body
   i++
   // body
}
```

How many times do we execute body?

Loop unrolling conditions

Let's examine this a bit closer?

```
for (int i = 0; i < 4; i++) {
   // body
}
```

```
for (int i = 0; i < 4; i++) {
   // body
   i++
   // body
   i++
   // body
}
```

What if we try to unroll this by a factor of 3?

How many times do we execute body?

what if we executed the unrolled loop as many times as it was valid, and did the rest with a non-unrolled loop

```
for (int i = ?; i < ?; i++) {
   // body
   i++
   // body
   i++
   // body
}
```

```
for (int i = ?; i < ?; i++) {
   // body
}
```

Loop unrolling conditions

initially the loop starts the same as the original loop

```
for (int i = 0; i < 4; i++) {
  // body
}
```

find out how many unrolled loops we can execute:
(4 / 3) * 3 = 3
This gives us the first bound

second loop is initialized with the first bound

second loop's bound is same as the original loop

what if we executed the unrolled loop as many times as it was valid, and did the rest with a non-unrolled loop

```
for (int i = ?; i < ?; i++) {
  // body
  i++
  // body
  i++
  // body
}
```

```
for (int i = ?; i < ?; i++) {
  // body
}
```

Loop unrolling conditions

What about in the general case? For unroll factor F?

```
for (int i = x; i < y; i++) {
   // body
}
```

find out how many unrolled loops we can execute:
?
This gives us the first bound

second loop is initialized with the first bound

second loop's bound is same as the original loop

what if we executed the unrolled loop as many times as it was valid, and did the rest with a non-unrolled loop

```
for (int i = ?; i < ?; i++) {
   // body
   i++
   ...
}
```

```
for (int i = ?; i < ?; i++) {
   // body
}
```

Loop unrolling conditions

- general unroll

For unroll factor F

General unroll constraints:
- Loop update increments by 1
- Find the concrete number of loop iterations, LI

General unroll code generation:
- Create simple unrolled loop with new bound: (LI/F)*F
- Create cleanup (basic) loop with initialization: (LI/F)*F
- perform codegen

None of these numbers have to be concrete!

More loop transforms

- Loop nesting order
- Loop tiling
- General area is called polyhedral compilation

https://en.wikipedia.org/wiki/Polytope_model

New constraints:

- Typically requires that loop iterations are independent
  - You can do the loop iterations in any order and get the same result

are these independent?

```
for (int i = 0; i < 2; i++) {
    counter += 1;
  }
```

vs

```
for (int i = 0; i < 1024; i++) {
    counter = i;
  }
```

Motivation:

Image processing

pretty straight
forward computation
for brightening

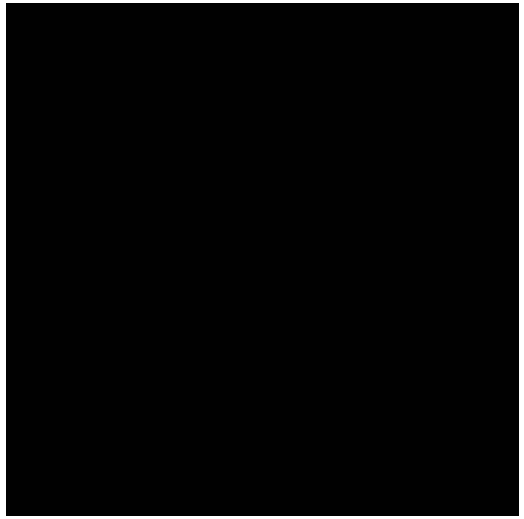
(1 pass over all pixels)

This computation is known as the “Local Laplacian Filter”. Requires visiting all pixels 99 times

We want to be able to do this
fast and efficiently!

Main results in from an image DSL show
a 1.7x speedup with 1/5 the LoC
over hand optimized versions at Adobe

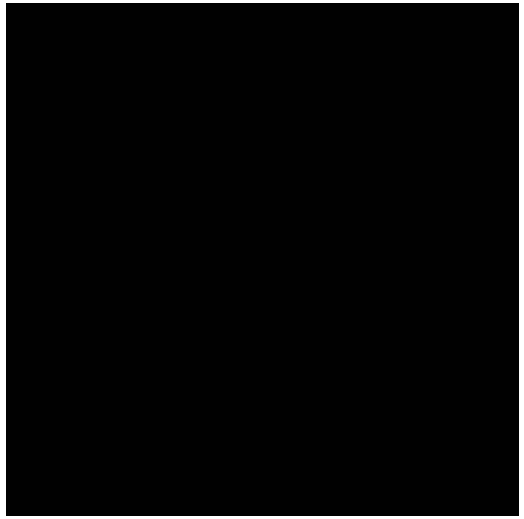
from: https://people.csail.mit.edu/sparis/publi/2011/siggraph/



```
for (int y = 0; y < 4; y++) {
    for (int x = 0; x < 4; x++) {
        output[y,x] = x + y;
    }
}
```

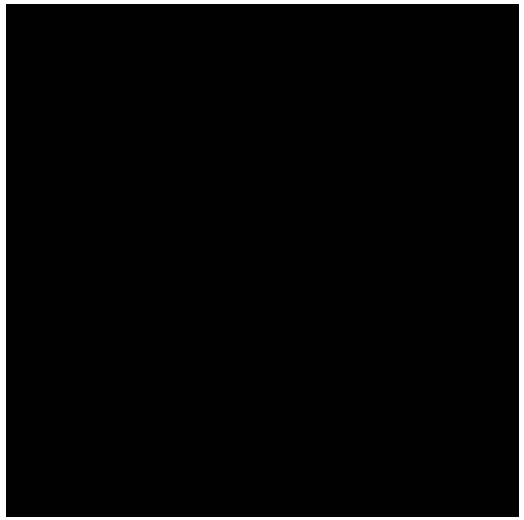
you can compute the pixels in any order you want, you just have to compute all of them!

from: https://halide-lang.org/tutorials/tutorial_lesson_05_scheduling_1.html



```
for (int y = 0; y < 4; y++) {
    for (int x = 0; x < 4; x++) {
        output[y,x] = x + y;
    }
}
```

you can compute the pixels in any order you want, you just have to compute all of them!



```
for (int x = 0; x < 4; x++) {
    for (int y = 0; y < 4; y++) {
        output[y,x] = x + y;
    }
}
```

What is the difference here? What will the difference be?

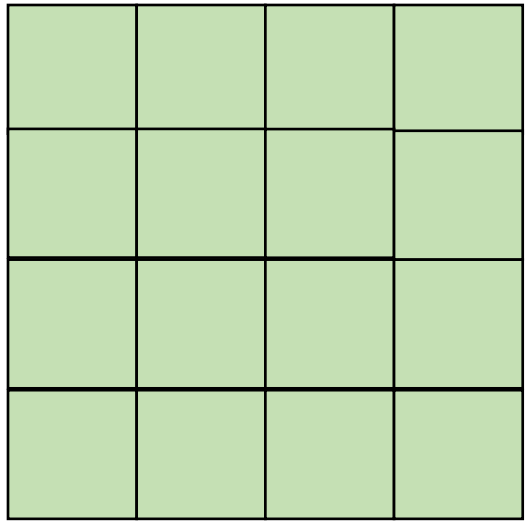
from: https://halide-lang.org/tutorials/tutorial_lesson_05_scheduling_1.html

Adding 2D arrays together

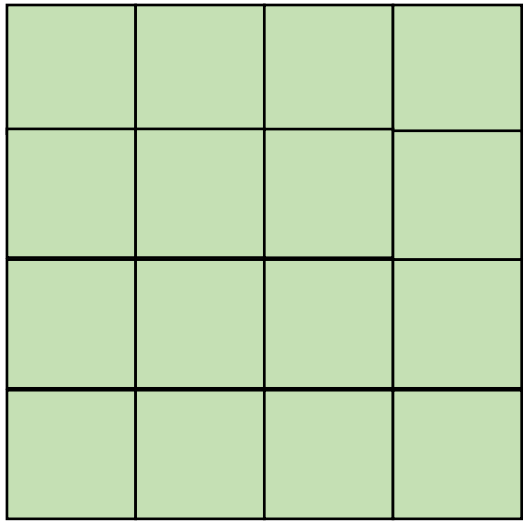
- Memory accesses

$$A = B + C$$

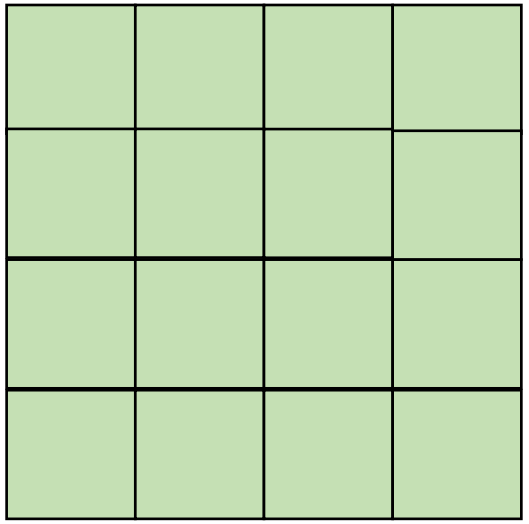
A



B



C



Demo

- Why do we see the performance difference?

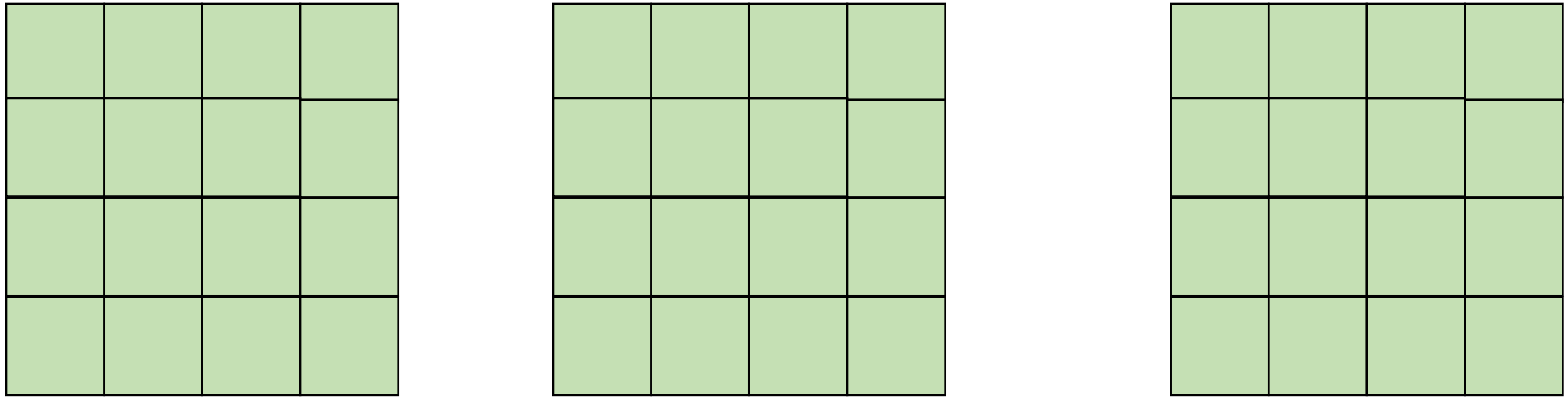
But sometimes there isn’t a good ordering

transposed arrays

- In some cases, there might not be a good nesting order for all accesses:

$$A = B + C^T$$

A B C

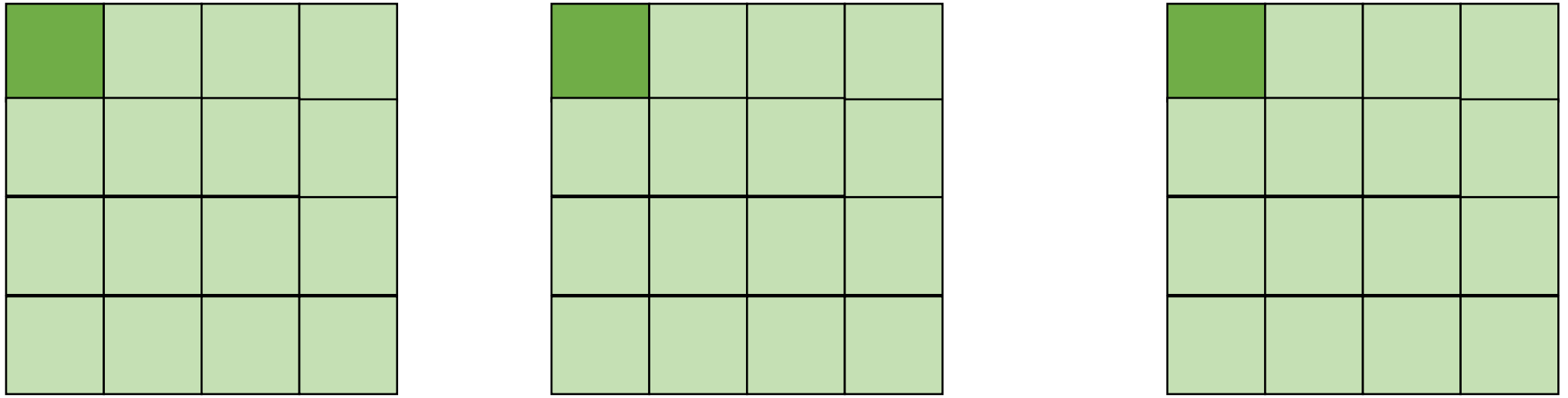


transposed arrays

- In some cases, there might not be a good nesting order for all accesses:

$$A = B + C^T$$

A B C



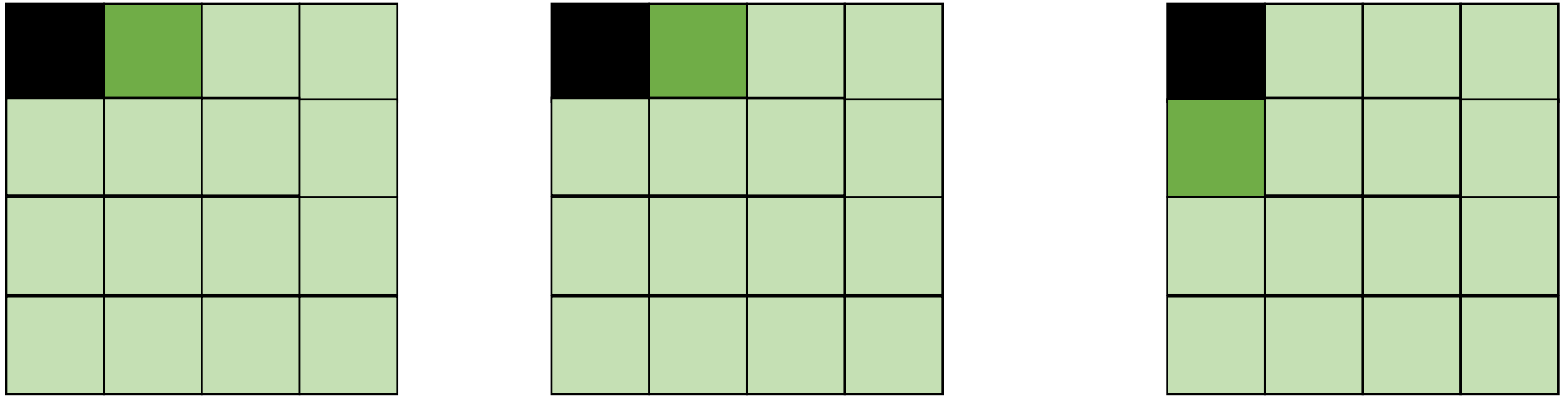
cold miss for all of them

transposed arrays

- In some cases, there might not be a good nesting order for all accesses:

$$A = B + C^T$$

A B C



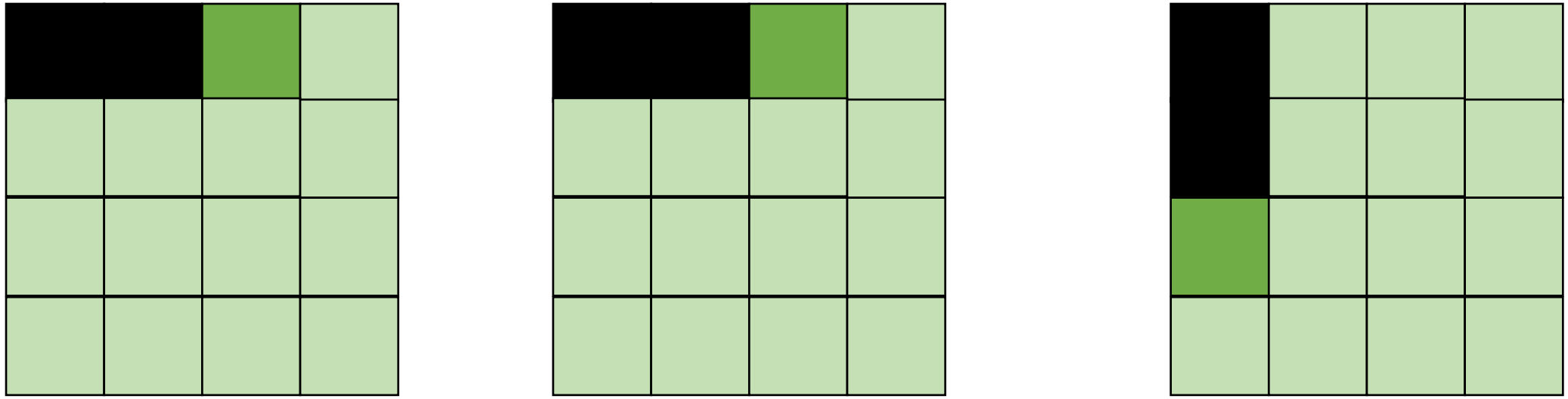
Hit on A and B. Miss on C

transposed arrays

- In some cases, there might not be a good nesting order for all accesses:

$$A = B + C^T$$

A B C



Hit on A and B. Miss on C

What happens here?

- Demo

How can we fix it?

- Can we use the compiler?

```
for (int y = 0; y < 4; y++) {
    for (int x = 0; x < 4; x++) {
        output[y,x] = x + y;
    }
}
```

Loop splitting:

```
for (int y = 0; y < 4; y++) {
    for (int x_outer = 0; x_outer < 4; x_outer+=2) {
        for (int x = x_outer; x < x_outer+2; x++) {
            output[y,x] = x + y;
        }
    }
}
```

What is the difference here?

from: https://halide-lang.org/tutorials/tutorial_lesson_05_scheduling_1.html

Does loop splitting by itself work?

- Lets try it
  - demo

We can chain optimizations

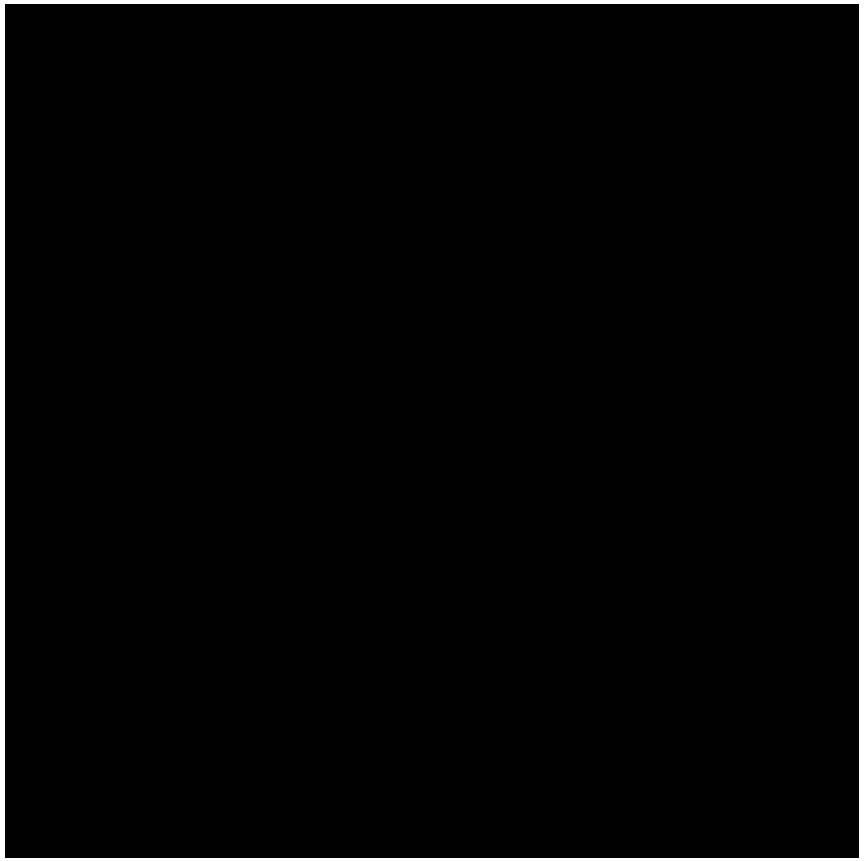
- Lets try chaining loop splitting and reorder
  - Demo

We can chain optimizations

- Lets try chaining loop splitting and reorder
  - Demo

- What happened?!

Our new schedule looks like this:



Why is this beneficial?

from: https://halide-lang.org/tutorials/tutorial_lesson_05_scheduling_1.html

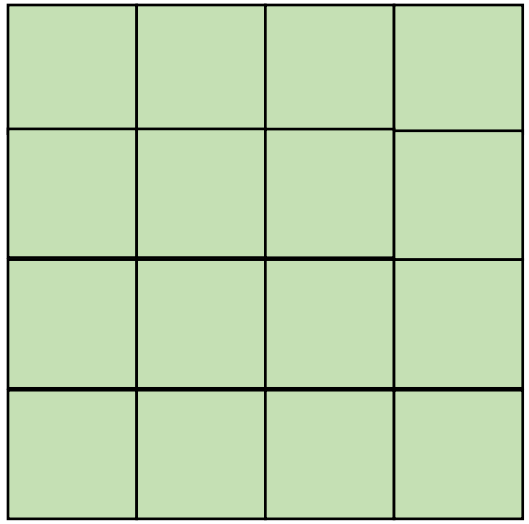
blocking

blocking

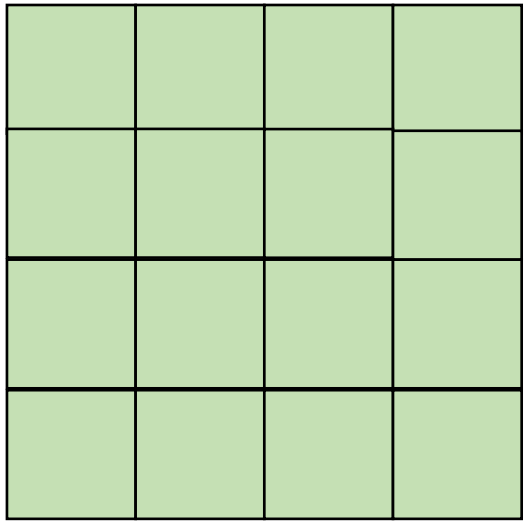
- Blocking operates on smaller chunks to exploit locality in column increment accesses. Example 2x2

$$A = B + C^T$$

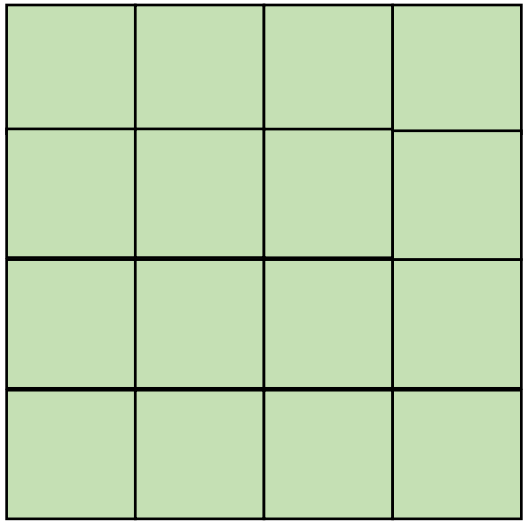
A



B



C

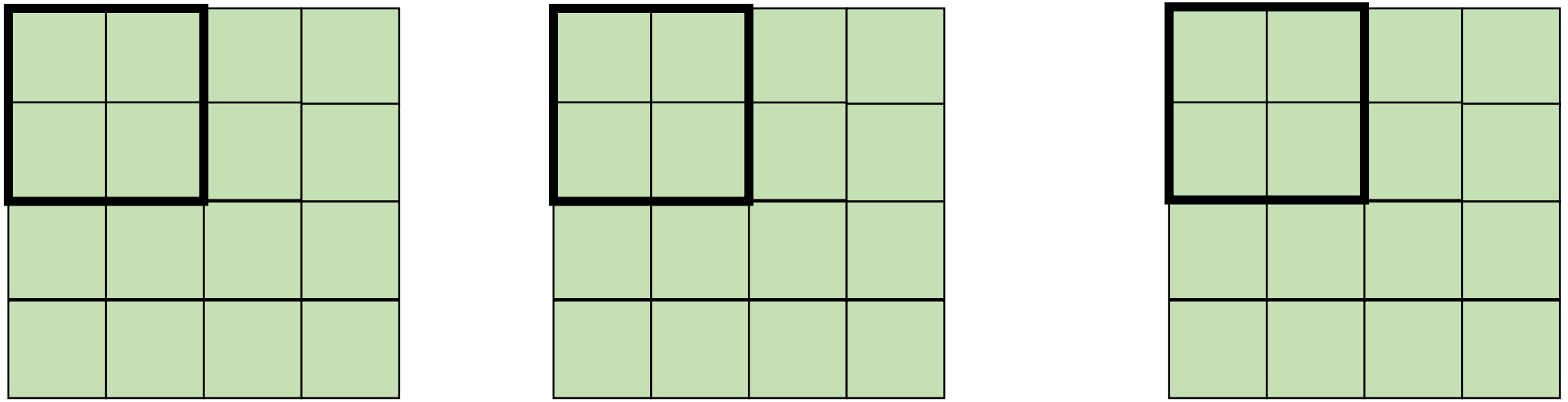


blocking

- Blocking operates on smaller chunks to exploit locality in column increment accesses. Example 2x2

$$A = B + C^T$$

A B C

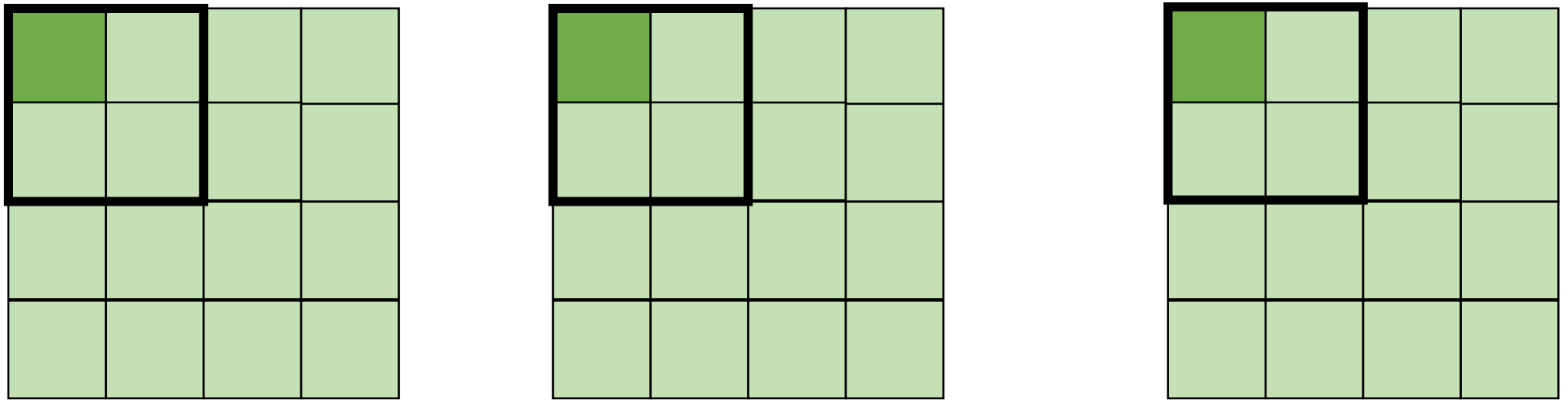


blocking

- Blocking operates on smaller chunks to exploit locality in column increment accesses. Example 2x2

$$A = B + C^T$$

A B C



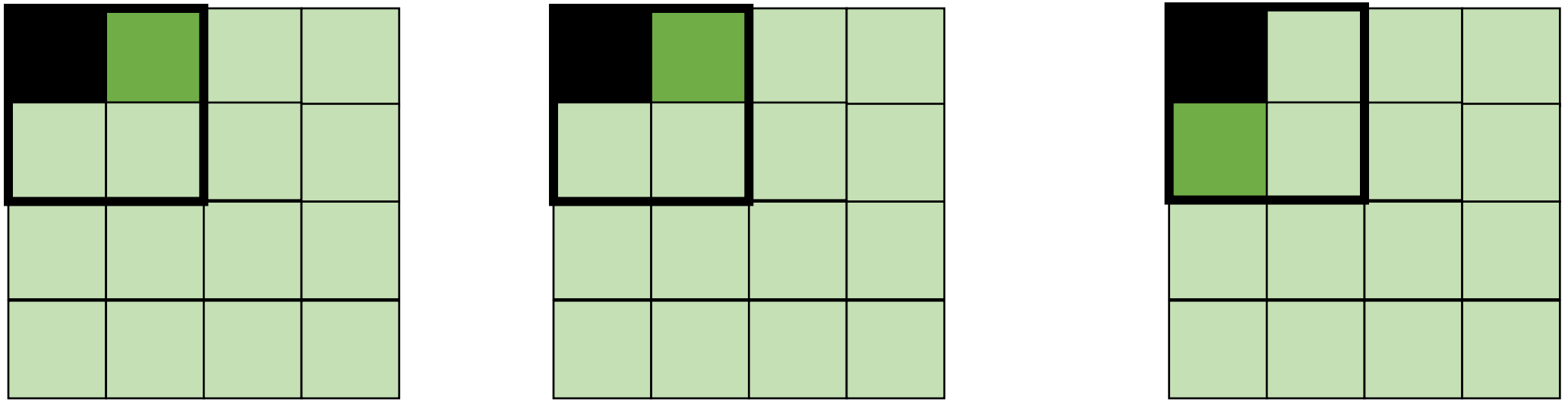
cold miss for all of them

blocking

- Blocking operates on smaller chunks to exploit locality in column increment accesses. Example 2x2

$$A = B + C^T$$

A B C



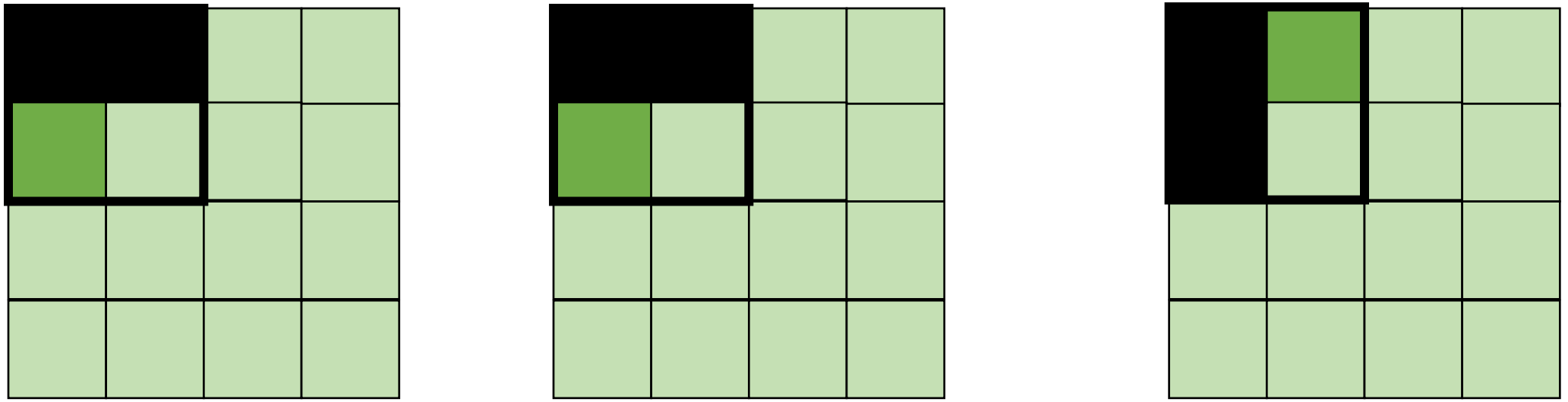
Miss on C

blocking

- Blocking operates on smaller chunks to exploit locality in column increment accesses. Example 2x2

$$A = B + C^T$$

A B C



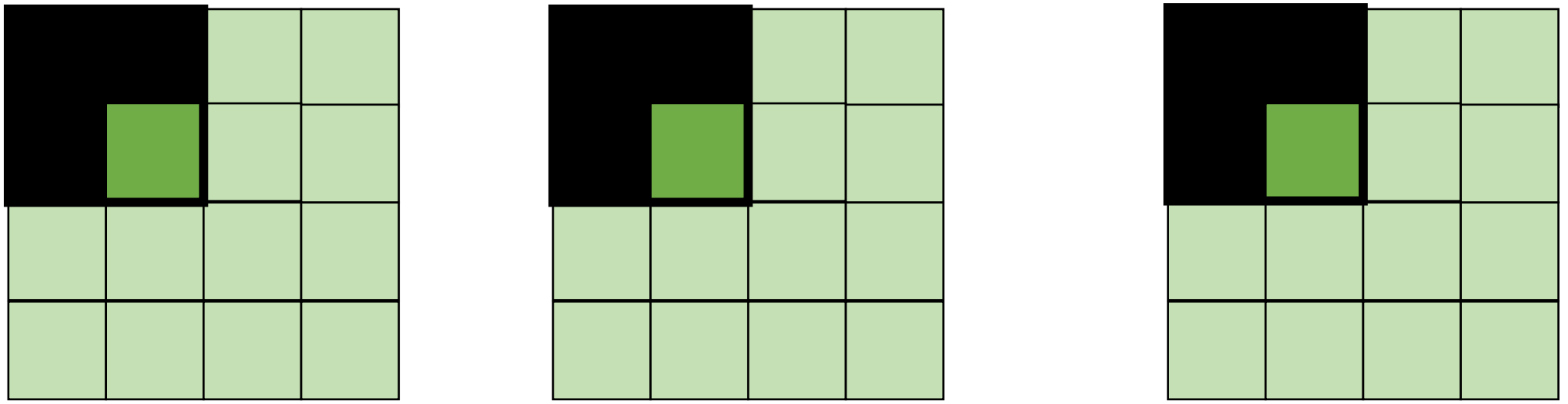
Miss on A,B, hit on C

blocking

- Blocking operates on smaller chunks to exploit locality in column increment accesses. Example 2x2

$$A = B + C^T$$

A B C



Hit on all!

See everyone on Monday

- More loop transformations