Performance Engineering of Software Systems

LECTURE 20

What Compilers Can and Cannot Do

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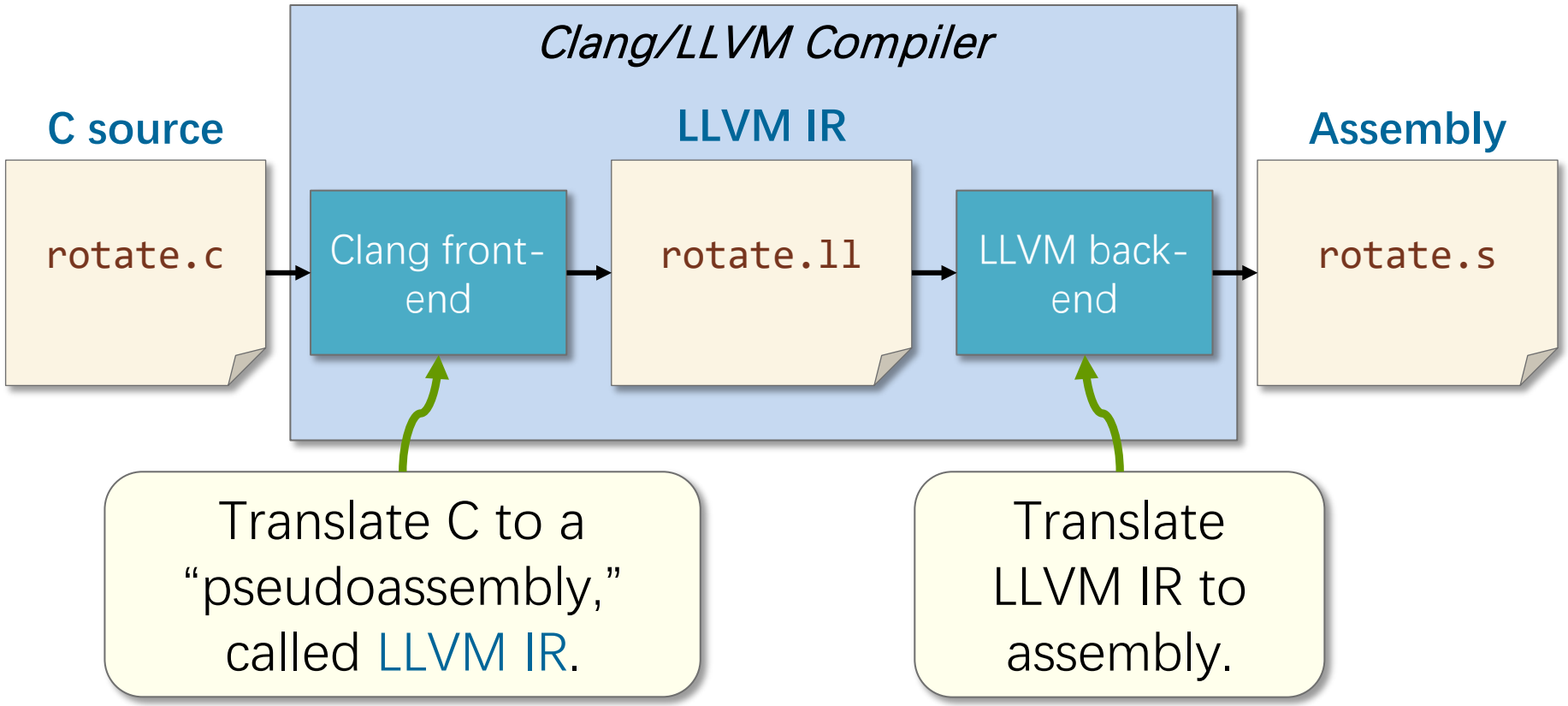
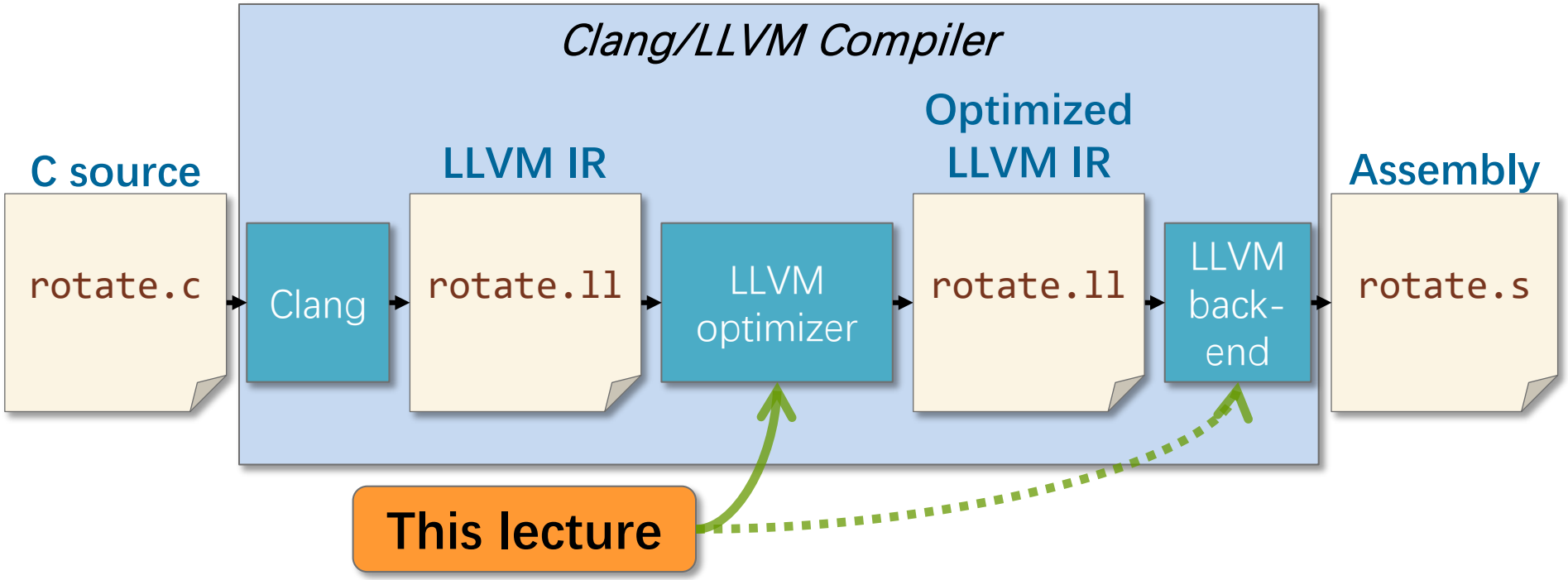
Clang/LLVM Compiler Pipeline

Recall Lecture 5: The basic compiler pipeline.

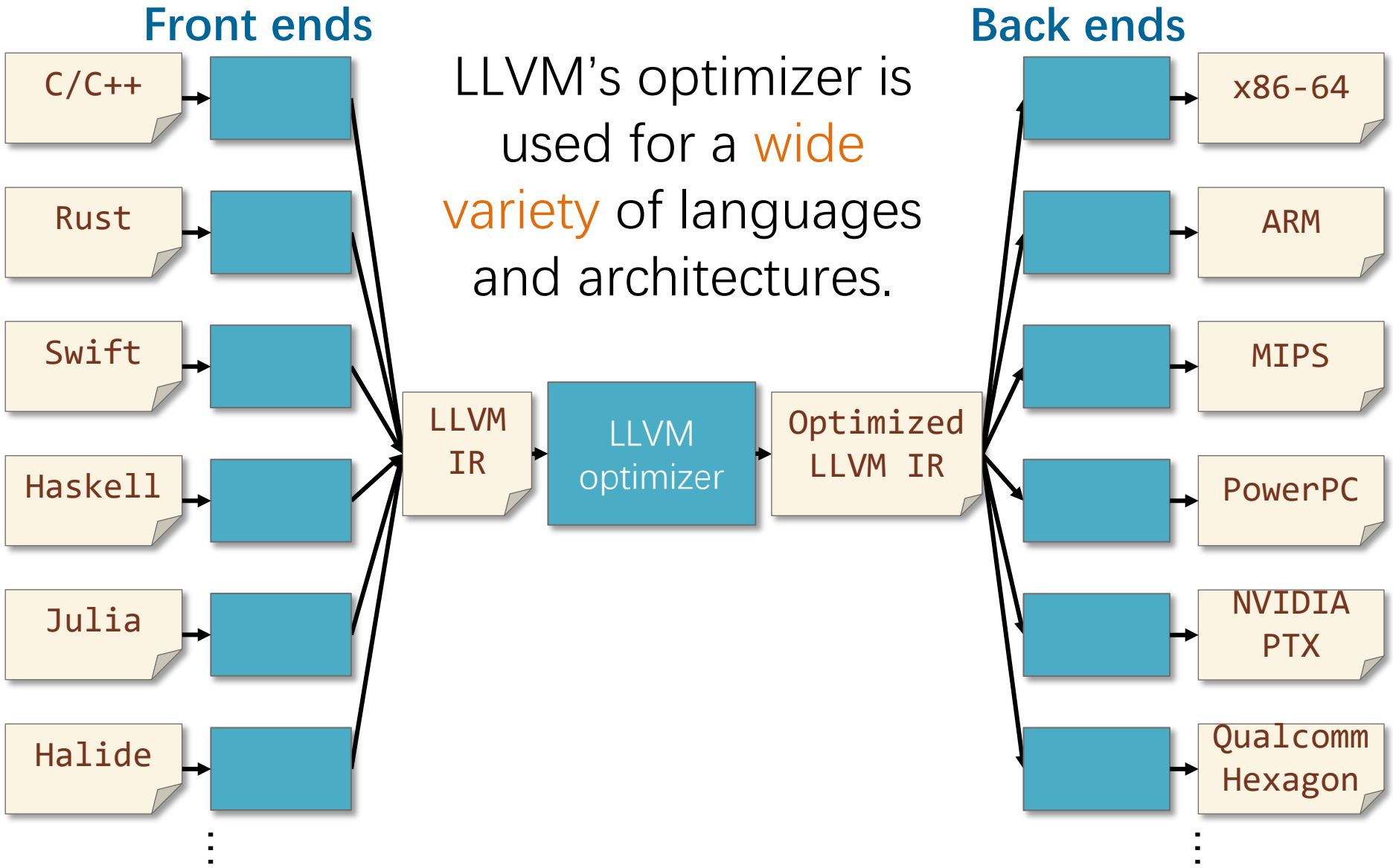


Clang/LLVM Compiler Pipeline Expanded

LLVM's optimizer transforms LLVM IR to make the resulting code run faster.



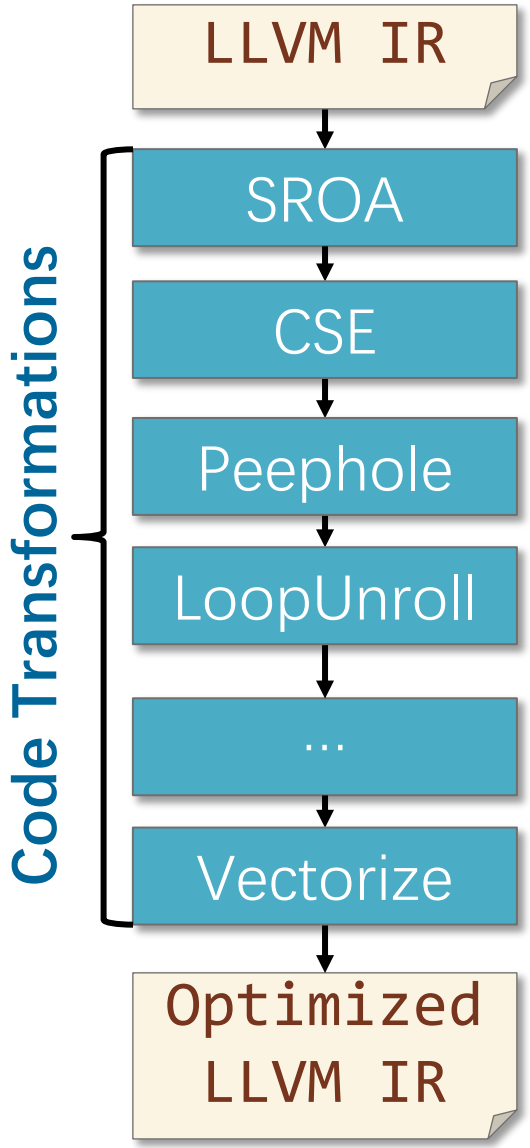
Larger Context of the Compiler



Why Study Compiler Optimizations?

- Compilers have a big impact on software performance.
- Compilers help ensure that simple, readable, and maintainable code is fast.
- You can understand the differences between the source code and the IR or assembly.
- Compilers can make mistakes.
- Compilers are conservative, thus notoriously finicky.
- Understanding compilers can help you use them more effectively.
- Even if they are temperamental, it's much easier to use a compiler than do the optimizations and transformations yourself!
- Compilers can save you performance-engineering work.

Simple Model of the Compiler



An optimizing compiler performs a sequence of **transformation passes** on the code.

- Each transformation pass analyzes and edits the code, typically to try to optimize the code's performance.
- A transformation pass might run multiple times.
- Passes run in a predetermined order that the compiler writers found works well most of the time.

Compiler Reports

Clang/LLVM can produce **reports** for many of its transformation passes, not just vectorization:

`-Rpass=<string>:` Produce reports of which optimizations matching `<string>` were successful.

`-Rpass-missed=<string>:` Produce reports of which optimizations matching `<string>` were not successful.

`-Rpass-analysis=<string>:` Produce reports of the analyses performed by optimizations matching `<string>`.

The argument `<string>` is a **regular expression**.
To see the whole report, use "`.*`" as the string.

An Example Compiler Report

```
$ clang -O3 -std=gnu11 -c CollisionWorld.c -Rpass=.* -Rpass-analysis=.*
…
CollisionWorld.c:92:39: remark: hoisting load [-Rpass=licm]
  for (int i = 0; i < collisionWorld->numOfLines; i++) {
                                      ^
CollisionWorld.c:91:6: remark: load of type i32 eliminated [-Rpass=gvn]
void CollisionWorld_lineWallCollision(CollisionWorld* collisionWorld) {
     ^
CollisionWorld.c:79:3: remark: CollisionWorld_lineWallCollision can be
inlined into CollisionWorld_updateLines with cost=245 (threshold=250)
[-Rpass-analysis=inline]
  CollisionWorld_lineWallCollision(collisionWorld);
  ^
CollisionWorld.c:79:3: remark: CollisionWorld_lineWallCollision inlined
into CollisionWorld_updateLines [-Rpass=inline]
CollisionWorld.c:135:5: remark: loop not vectorized: loop control flow
is not understood by vectorizer [-Rpass-analysis=loop-vectorize]
    for (int j = i + 1; j < collisionWorld->numOfLines; j++) {
    ^
…
```

Compiler Reports: Good and Bad

GOOD NEWS: The compiler can tell you a lot about what it's doing.

- Many transformation passes in LLVM can report places where they successfully transform code.
- Many can also report the conclusions of their analysis.

BAD NEWS: Reports can be hard to understand.

- The reports can be long and use LLVM jargon.
- Not all transformation passes generate reports.
- Reports can be misleading and don't always tell the whole story.

We want context for understanding these reports.

Outline

- Overview of compiler optimizations
- Examples of compiler optimizations
  - Scalar optimizations
  - Optimizing structure usage
  - Function inlining
- Case studies

Overview of Compiler Optimizations

~~New Bentley Rules~~ Compiler Optimizations

Data structures

- Register allocation
- Replace memory with registers
- Replace aggregates with scalars
- Data alignment

Loops

- Hoisting
- ~~Sentinels~~
- Loop unrolling
- Loop fusion *
- Eliminating wasted iterations *

Logic

- Constant folding and propagation
- Common-subexpression elimination
- Algebraic identities
- ~~Creating a fast path~~
- Short-circuiting
- Ordering tests *
- Combining tests *

Functions

- Inlining
- Tail-recursion elimination

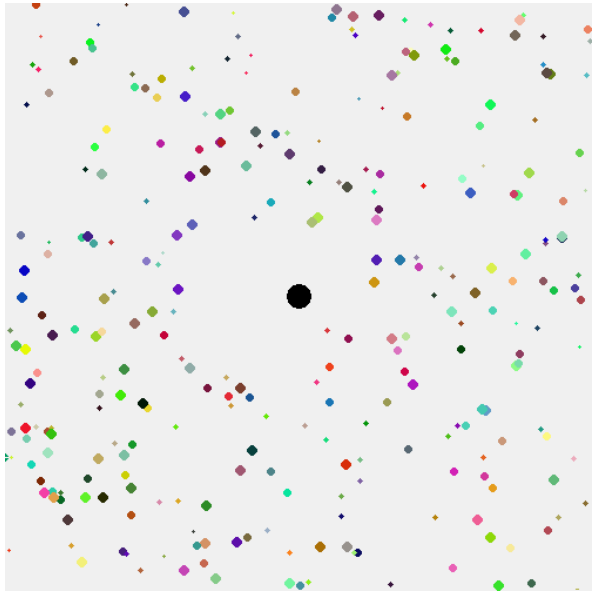
Moving target: Compiler developers implement new optimizations over time.

*Restrictions may apply.

Examples of Compiler Optimizations

Example: N-Body Simulation

PROBLEM: Simulate the behavior of n massive bodies in 2D space under the influence of gravity.



LAW OF GRAVITATION:

$\mathbf{F}_{21} = (G\, m_1 m_2 / |\mathbf{r}_{12}|^2)\ \text{unit}(\mathbf{r}_{21})$

KEY STEP: For each body, use the force acting on that body to update its position and velocity.

Let's look at a few different implementations to see how compiler optimizations affect how we can write this code.

Abstract Implementation

```
void update_positions(int nbodies, body_t *bodies,
                      double time_quantum) {

  for (/* Each body */) {
    // Compute the new vel                ody.


    // Update the position of ith body based on
    // the average of its old and new velocity.


    // Set the new velocity of ith body.


  }
}
```

Number of bodies

Abstract Implementation

```
void update_positions(int nbodies, body_t *bodies,
                      double time_quantum) {

  for (/* Each body */) {
    // Compute the new veloc

    // Update the position of ith body based on
    // the average of its old and new velocity.


    // Set the new velocity of ith body.


  }
}
```

Array storing force, velocity, position, and mass of each body.

Abstract Implementation

```
void update_positions(int nbodies, body_t *bodies,
                      double time_quantum) {

  for (/* Each body */) {
    // Compute the new veloc

    // Update the position of ith body based on
    // the average of its old and new velocity.

    // Set the new velocity of ith body.

  }
}
```

Length of time that modeled by one step of the simulation.

Abstract Implementation

```
void update_positions(int nbodies, body_t *bodies,
                      double time_quantum) {

  for (/* Each body */) {
    // Compute the new velocity of ith body.


    // Update the position of ith body based on
    // the average of its old and new velocity.


    // Set the new velocity of ith body.


  }
}
```

Let's look at a few different implementations of this function.

Starting point: A fast baseline that uses abstractions minimally.

Implementation 1: Explicit

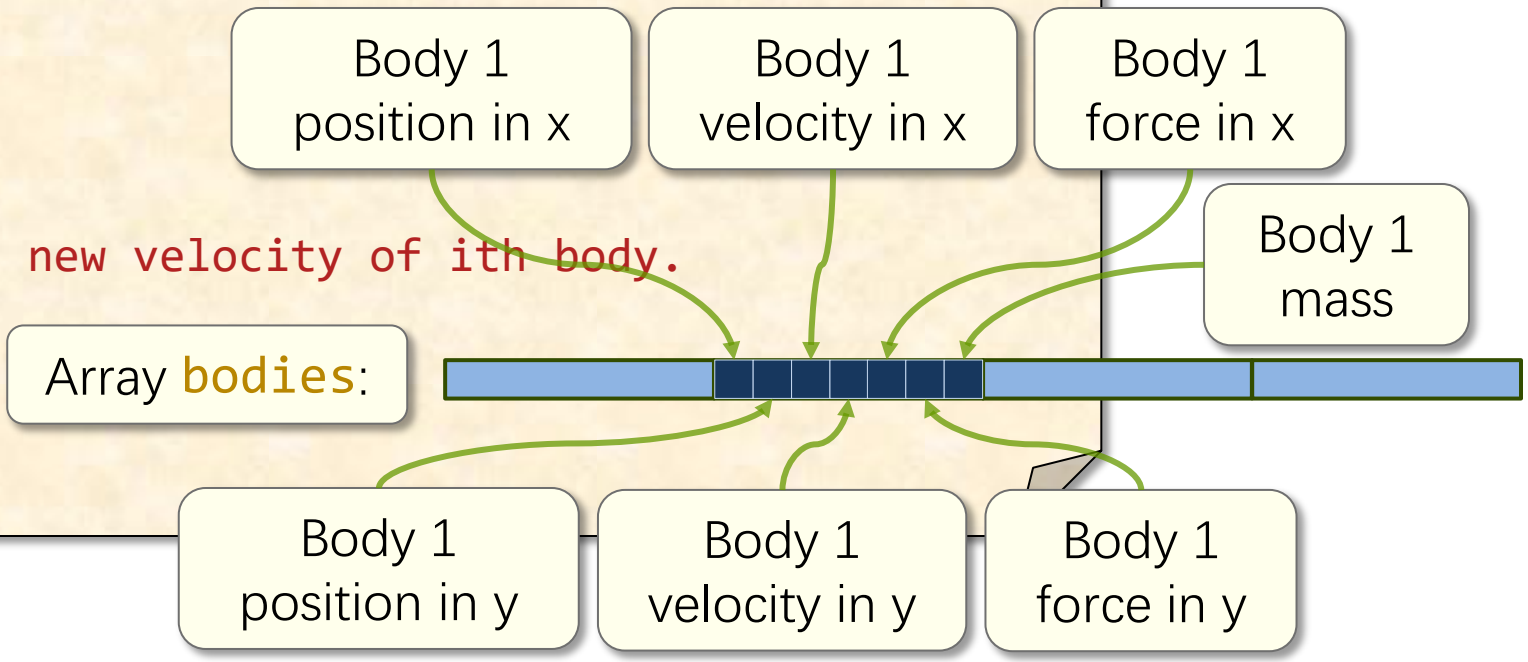
```
void update_positions(int nbodies, double *bodies,
                      double time_quantum) {
  for (
    // Compute the new velocity of ith

    // Update the position of ith body
    // the average of its old and new velocity.

    // Set the new velocity of ith body.

  }
}
```

Simple representation:
Every 7 consecutive doubles stores the position, velocity, force, and mass of 1 body.



Implementation 1: Explicit

```
void update_positions(int nbodies, double *bodies,
                      double time_quantum) {
  for (int i = 0; i < 7 * nbodies; i += 7) {
    // Compute the new velocity of ith body.




    // Update the position of ith body based on
    // the average of its old and new velocity.




    // Set the new velocity of ith body.


  }
}
```

Loop over the bodies.

Implementation 1: Explicit

```
void update_positions(int nbodies, double *bodies,
                      double time_quantum) {
    for (int i = 0; i < 7 * nbodies; i += 7) {
        // Compute the new velocity of ith body.
        double new_velocity_x = bodies[i + 4] *
            (time_quantum / bodies[i + 6]);
        double new_velocity_y = bodies[i + 5] *
            (time_quantum / bodies[i + 6]);
        // Update the position of ith body based on
        // average of its old and new velocity.
        ...
        // Set the new velocity of ith body.
        ...
    }
}
```

Force in x

Force in y

Mass

Compute new velocity as force times time quantum divided by mass.

Implementation 1: Explicit

```
void update_positions(int nbodies, double *bodies,
                      double time_quantum) {
  for (int i = 0; i < 7 * nbodies; i += 7) {
    // Compute the new velocity of ith body.
    double new_velocity_x = bodies[i + 4] *
        (time_quantum / bodies[i + 6]);
    double new_velocity_y = bodies[i + 5] *
        (time_quantum / bodies[i + 6]);
    // Update the position of ith body based on
    // the average of its old and new velocity.
    bodies[i] += (bodies[i + 2] + new_velocity_x) *
                 (time_quantum / 2.0);
    bodies[i + 1] += (bodies[i + 3] + new_velocity_y) *
                     (time_quantum / 2.0);
    // Set the new velocity of ith body.


  }
}
```

Update position using average velocity and time quantum.

Position in x

Position in y

Previous velocity in x

Previous velocity in y

Implementation 1: Explicit

```
void update_positions(int nbodies, double *bodies,
                      double time_quantum) {
  for (int i = 0; i < 7 * nbodies; i += 7) {
    // Compute the new velocity of ith body.
    double new_velocity_x = bodies[i + 4] *
        (time_quantum / bodies[i + 6]);
    double new_velocity_y = bodies[i + 5] *
        (time_quantum / bodies[i + 6]);
    // Update the position of ith body based on
    // the average of its old and new velocity.
    bodies[i] += (bodies[i + 2] + new_velocity_x) *
                 (time_quantum / 2.0);
    bodies[i + 1] += (bodies[i + 3] + new_velocity_y) *
                     (time_quantum / 2.0);
    // Set the new velocity of ith body.
    bodies[i + 2] = new_velocity_x;
    bodies[i + 3] = new_velocity_y;
  }
}
```

Store new velocities

Scalar Optimizations

Implementation 1: Explicit

Let's see how the compiler optimizes this code (aside from vectorization).

```
void update_positions(int nbodies, double *bodies,
                      double time_quantum) {
  for (int i = 0; i < 7 * nbodies; i += 7) {
    // Compute the new velocity of ith body.
    double new_velocity_x = bodies[i + 4] *
        (time_quantum / bodies[i + 6]);
    double new_velocity_y = bodies[i + 5] *
        (time_quantum / bodies[i + 6]);
    // Update the position of ith body based on
    // the average of its old and new velocity.
    bodies[i] += (bodies[i + 2] + new_velocity_x) *
                 (time_quantum / 2.0);
    bodies[i + 1] += (bodies[i + 3] + new_velocity_y) *
                     (time_quantum / 2.0);
    // Set the new velocity of ith body.
    bodies[i + 2] = new_velocity_x;
    bodies[i + 3] = new_velocity_y;
  }
}
```

First focus

Second focus

LLVM IR for Implementation 1

C

```
void update_positions(
    int nbodies,
    double *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    double new_velocity_x =
      bodies[i + 4] *
      (time_quantum /
       bodies[i + 6]);
    double new_velocity_y =
      bodies[i + 5] *
      (time_quantum /
       bodies[i + 6]);
    // …
  }
}
```

LLVM IR

```
%12 = add nuw nsw i64 %11, 4
%13 = getelementptr inbounds double,
    double* %1, i64 %12
%14 = load double, double* %13, align 8
%15 = add nuw nsw i64 %11, 6
%16 = getelementptr inbounds double,
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%19 = fmul double %14, %18
%20 = add nuw nsw i64 %11, 5
%21 = getelementptr inbounds double,
    double* %1, i64 %20
%22 = load double, double* %21, align 8
%23 = add nuw nsw i64 %11, 6
%24 = getelementptr inbounds double,
    double* %1, i64 %23
%25 = load double, double* %24, align 8
%26 = fdiv double %2, %25
%27 = fmul double %22, %26
```

Note: This LLVM IR has been partially optimized for brevity.

LLVM IR for Implementation 1

C

```
void update_positions(
    int nbodies,
    double *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    double new_velocity_x =
      bodies[i + 4] *
      (time_quantum /
       bodies[i + 6]);
    double new_velocity_y =
      bodies[i + 5] *
      (time_quantum /
       bodies[i + 6]);
    // …
  }
}
```

Register %11 stores i.

LLVM IR

```
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```

LLVM IR for Implementation 1

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void update_positions(
    int nbodies,
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    double time_quantum) {
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       bodies[i + 6]);
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      (time_quantum /
       bodies[i + 6]);
    // …
  }
}
```

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       bodies[i + 6]);
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       bodies[i + 6]);
    // …
  }
}
```

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LLVM IR

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%12 = add nuw nsw i64 %11, 4
%13 = getelementptr inbounds double,
    double* %1, i64 %12
%14 = load double, double* %13, align 8
%15 = add nuw nsw i64 %11, 6
%16 = getelementptr inbounds double,
    double* %1, i64 %15
%17 = load double, double* %16, align 8
%18 = fdiv double %2, %17
%19 = fmul double %14, %18
%20 = add nuw nsw i64 %11, 5
%21 = getelementptr inbounds double,
    double* %1, i64 %20
%22 = load double, double* %21, align 8
%23 = add nuw nsw i64 %11, 6
%24 = getelementptr inbounds double,
    double* %1, i64 %23
%25 = load double, double* %24, align 8
%26 = fdiv double %2, %25
%27 = fmul double %22, %26
```

Optimizing Implementation 1

C

```
void update_positions(
    int nbodies,
    double *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    double new_velocity_x =
      bodies[i + 4] *
      (time_quantum /
       bodies[i + 6]);
    double new_velocity_y =
      bodies[i + 5] *
      (time_quantum /
       bodies[i + 6]);
    // …
  }
}
```

LLVM IR

```
%12 = add nuw nsw i64 %11, 4
%13 = getelementptr inbounds double,
    double* %1, i64 %12
%14 = load double, double* %13, align 8
%15 = add nuw nsw i64 %11, 6
%16 = getelementptr inbounds double,
    double* %1, i64 %15
%17 = load double, double* %16, align 8
%18 = fdiv double %2, %17
%19 = fmul double %14, %18
%20 = add nuw nsw i64 %11, 5
%21 = getelementptr inbounds double,
    double* %1, i64 %20
%22 = load double, double* %21, align 8
%23 = add nuw nsw i64 %11, 6
%24 = getelementptr inbounds double,
    double* %1, i64 %23
%25 = load double, double* %24, align 8
%26 = fdiv double %2, %25
%27 = fmul double %22, %26
```

%17

Eliminate the common subexpression!

Optimizing Implementation 1

C

```
void update_positions(
    int nbodies,
    double *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    double new_velocity_x =
      bodies[i + 4] *
      (time_quantum /
       bodies[i + 6]);
    double new_velocity_y =
      bodies[i + 5] *
      (time_quantum /
       bodies[i + 6]);
    // …
  }
}
```

LLVM IR

```
%12 = add nuw nsw i64 %11, 4
%13 = getelementptr inbounds double,
    double* %1, i64 %12
%14 = load double, double* %13, align 8
%15 = add nuw nsw i64 %11, 6
%16 = getelementptr inbounds double,
    double* %1, i64 %15
%17 = load double, double* %16, align 8
%18 = fdiv double %2, %17
%19 = fmul double %14, %18
%20 = add nuw nsw i64 %11, 5
%21 = getelementptr inbounds double,
    double* %1, i64 %20
%22 = load double, double* %21, align 8

%23 = fdiv double %2, %17
%24 = fmul double %22, %23
```

%18

Eliminate the common subexpression!

Optimizing Implementation 1: Result

C

```
void update_positions(
    int nbodies,
    double *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    double new_velocity_x =
      bodies[i + 4] *
      (time_quantum /
       bodies[i + 6]);
    double new_velocity_y =
      bodies[i + 5] *
      (time_quantum /
       bodies[i + 6]);
    // …
  }
}
```

LLVM IR

```
%12 = add nuw nsw i64 %11, 4
%13 = getelementptr inbounds double,
    double* %1, i64 %12
%14 = load double, double* %13, align 8
%15 = add nuw nsw i64 %11, 6
%16 = getelementptr inbounds double,
    double* %1, i64 %15
%17 = load double, double* %16, align 8
%18 = fdiv double %2, %17
%19 = fmul double %14, %18
%20 = add nuw nsw i64 %11, 5
%21 = getelementptr inbounds double,
    double* %1, i64 %20
%22 = load double, double* %21, align 8
%23 = fmul double %22, %18
```

LLVM IR for Implementation 1, Cont'd

C

```
void update_positions(
    int nbodies,
    double *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    // …
    bodies[i] +=
      (bodies[i + 2] +
       new_velocity_x) *
      (time_quantum/2.0);
    bodies[i + 1] +=
      (bodies[i + 3] +
       new_velocity_y) *
      (time_quantum/2.0);
    // …
  }
}
```

Register %11 stores i.

LLVM IR

```
5:                                ; preds = %3
  …
  br label %10

10:                               ; preds = %5, %10
  …
  %24 = add nuw nsw i64 %11, 2
  %25 = getelementptr inbounds double,
    double* %1, i64 %24
  %26 = load double, double* %25, align 8
  %27 = fadd double %26, %19
  %28 = fdiv double %2, 2.000000e+00
  %29 = fmul double %28, %27
  …
  %32 = add nuw nsw i64 %11, 3
  %33 = getelementptr inbounds double,
    double* %1, i64 %32
  %34 = load double, double* %33, align 8
  %35 = fadd double %23, %34
  %36 = fdiv double %2, 2.000000e+00
  %37 = fmul double %36, %35
  …
  br i1 %42, label %10, label %9, !llvm.loop !9
```

LLVM IR for Implementation 1, Cont'd

C

```
void update_positions(
    int nbodies,
    double *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    // …
    bodies[i] +=
      (bodies[i + 2] +
       new_velocity_x) *
      (time_quantum/2.0);
    bodies[i + 1] +=
      (bodies[i + 3] +
       new_velocity_y) *
      (time_quantum/2.0);
    // …
  }
}
```

LLVM IR

```
5:                                ; preds = %3
  …
  br label %10

10:                               ; preds = %5, %10
  …
  %24 = add nuw nsw i64 %11, 2
  %25 = getelementptr inbounds double,
    double* %1, i64 %24
  %26 = load double, double* %25, align 8
  %27 = fadd double %26, %19
  %28 = fdiv double %2, 2.000000e+00
  %29 = fmul double %28, %27
  …
  %32 = add nuw nsw i64 %11, 3
  %33 = getelementptr inbounds double,
    double* %1, i64 %32
  %34 = load double, double* %33, align 8
  %35 = fadd double %23, %34
  %36 = fdiv double %2, 2.000000e+00
  %37 = fmul double %36, %35
  …
  br i1 %42, label %10, label %9, !llvm.loop !9
```

LLVM IR for Implementation 1, Cont'd

C

```
void update_positions(
    int nbodies,
    double *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    // …
    bodies[i] +=
      (bodies[i + 2] +
       new_velocity_x) *
      (time_quantum/2.0);
    bodies[i + 1] +=
      (bodies[i + 3] +
       new_velocity_y) *
      (time_quantum/2.0);
    // …
  }
}
```

LLVM IR

```
5:                                ; preds = %3
  …
  br label %10

10:                               ; preds = %5, %10
  …
  %24 = add nuw nsw i64 %11, 2
  %25 = getelementptr inbounds double,
    double* %1, i64 %24
  %26 = load double, double* %25, align 8
  %27 = fadd double %26, %19
  %28 = fdiv double %2, 2.000000e+00
  %29 = fmul double %28, %27
  …
  %32 = add nuw nsw i64 %11, 3
  %33 = getelementptr inbounds double,
    double* %1, i64 %32
  %34 = load double, double* %33, align 8
  %35 = fadd double %23, %34
  %36 = fdiv double %2, 2.000000e+00
  %37 = fmul double %36, %35
  …
  br i1 %42, label %10, label %9, !llvm.loop !9
```

LLVM IR for Implementation 1, Cont'd

C

```
void update_positions(
    int nbodies,
    double *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    // …
    bodies[i] +=
      (bodies[i + 2] +
       new_velocity_x) *
      (time_quantum/2.0);
    bodies[i + 1] +=
      (bodies[i + 3] +
       new_velocity_y) *
      (time_quantum/2.0);
    // …
  }
}
```

LLVM IR

```
5:                                ; preds = %3
  …
  br label %10

10:                               ; preds = %5, %10
  …
  %24 = add nuw nsw i64 %11, 2
  %25 = getelementptr inbounds double,
    double* %1, i64 %24
  %26 = load double, double* %25, align 8
  %27 = fadd double %26, %19
  %28 = fdiv double %2, 2.000000e+00
  %29 = fmul double %28, %27
  …
  %32 = add nuw nsw i64 %11, 3
  %33 = getelementptr inbounds double,
    double* %1, i64 %32
  %34 = load double, double* %33, align 8
  %35 = fadd double %23, %34
  %36 = fdiv double %2, 2.000000e+00
  %37 = fmul double %36, %35
  …
  br i1 %42, label %10, label %9, !llvm.loop !9
```

LLVM IR for Implementation 1, Cont'd

C

```
void update_positions(
    int nbodies,
    double *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    // …
    bodies[i] +=
      (bodies[i + 2] +
       new_velocity_x) *
      (time_quantum/2.0);
    bodies[i + 1] +=
      (bodies[i + 3] +
       new_velocity_y) *
      (time_quantum/2.0);
    // …
  }
}
```

LLVM IR

```
5:                                ; preds = %3
  …
  br label %10

10:                               ; preds = %5, %10
  …
  %24 = add nuw nsw i64 %11, 2
  %25 = getelementptr inbounds double,
    double* %1, i64 %24
  %26 = load double, double* %25, align 8
  %27 = fadd double %26, %19
  %28 = fdiv double %2, 2.000000e+00
  %29 = fmul double %28, %27
  …
  %32 = add nuw nsw i64 %11, 3
  %33 = getelementptr inbounds double,
    double* %1, i64 %32
  %34 = load double, double* %33, align 8
  %35 = fadd double %23, %34
  %36 = fdiv double %2, 2.000000e+00
  %37 = fmul double %36, %35
  …
  br i1 %42, label %10, label %9, !llvm.loop !9
```

LLVM IR for Implementation 1, Cont'd

C

```
void update_positions(
    int nbodies,
    double *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    // …
    bodies[i] +=
      (bodies[i + 2] +
       new_velocity_x) *
      (time_quantum/2.0);
    bodies[i + 1] +=
      (bodies[i + 3] +
       new_velocity_y) *
      (time_quantum/2.0);
    // …
  }
}
```

LLVM IR

```
5:                                ; preds = %3
  …
  br label %10

10:                               ; preds = %5, %10
  …
  %24 = add nuw nsw i64 %11, 2
  %25 = getelementptr inbounds double,
    double* %1, i64 %24
  %26 = load double, double* %25, align 8
  %27 = fadd double %26, %19
  %28 = fdiv double %2, 2.000000e+00
  %29 = fmul double %28, %27
  …
  %32 = add nuw nsw i64 %11, 3
  %33 = getelementptr inbounds double,
    double* %1, i64 %32
  %34 = load double, double* %33, align 8
  %35 = fadd double %23, %34
  %36 = fdiv double %2, 2.000000e+00
  %37 = fmul double %36, %35
  …
  br i1 %42, label %10, label %9, !llvm.loop !9
```

LLVM IR for Implementation 1, Cont'd

C

```
void update_positions(
    int nbodies,
    double *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    // …
    bodies[i] +=
      (bodies[i + 2] +
       new_velocity_x) *
      (time_quantum/2.0);
    bodies[i + 1] +=
      (bodies[i + 3] +
       new_velocity_y) *
      (time_quantum/2.0);
    // …
  }
}
```

LLVM IR

```
5:                                ; preds = %3
  …
  br label %10

10:                               ; preds = %5, %10
  …
  %24 = add nuw nsw i64 %11, 2
  %25 = getelementptr inbounds double,
    double* %1, i64 %24
  %26 = load double, double* %25, align 8
  %27 = fadd double %26, %19
  %28 = fdiv double %2, 2.000000e+00
  %29 = fmul double %28, %27
  …
  %32 = add nuw nsw i64 %11, 3
  %33 = getelementptr inbounds double,
    double* %1, i64 %32
  %34 = load double, double* %33, align 8
  %35 = fadd double %23, %34
  %36 = fdiv double %2, 2.000000e+00
  %37 = fmul double %36, %35
  …
  br i1 %42, label %10, label %9, !llvm.loop !9
```

LLVM IR for Implementation 1, Cont'd

C

```
void update_positions(
    int nbodies,
    double *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    // …
    bodies[i] +=
      (bodies[i + 2] +
       new_velocity_x) *
      (time_quantum/2.0);
    bodies[i + 1] +=
      (bodies[i + 3] +
       new_velocity_y) *
      (time_quantum/2.0);
    // …
  }
}
```

LLVM IR

```
5:                                ; preds = %3
  …
  br label %10

10:                               ; preds = %5, %10
  …
  %24 = add nuw nsw i64 %11, 2
  %25 = getelementptr inbounds double,
    double* %1, i64 %24
  %26 = load double, double* %25, align 8
  %27 = fadd double %26, %19
  %28 = fdiv double %2, 2.000000e+00
  %29 = fmul double %28, %27
  …
  %32 = add nuw nsw i64 %11, 3
  %33 = getelementptr inbounds double,
    double* %1, i64 %32
  %34 = load double, double* %33, align 8
  %35 = fadd double %23, %34
  %36 = fdiv double %2, 2.000000e+00
  %37 = fmul double %36, %35
  …
  br i1 %42, label %10, label %9, !llvm.loop !9
```

LLVM IR for Implementation 1, Cont'd

C

```
void update_positions(
    int nbodies,
    double *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    // …
    bodies[i] +=
      (bodies[i + 2] +
       new_velocity_x) *
      (time_quantum/2.0);
    bodies[i + 1] +=
      (bodies[i + 3] +
       new_velocity_y) *
      (time_quantum/2.0);
    // …
  }
}
```

LLVM IR

```
5:                                ; preds = %3
  …
  br label %10

10:                               ; preds = %5, %10
  …
  %24 = add nuw nsw i64 %11, 2
  %25 = getelementptr inbounds double,
    double* %1, i64 %24
  %26 = load double, double* %25, align 8
  %27 = fadd double %26, %19
  %28 = fdiv double %2, 2.000000e+00
  %29 = fmul double %28, %27
  …
  %32 = add nuw nsw i64 %11, 3
  %33 = getelementptr inbounds double,
    double* %1, i64 %32
  %34 = load double, double* %33, align 8
  %35 = fadd double %23, %34
  %36 = fdiv double %2, 2.000000e+00
  %37 = fmul double %36, %35
  …
  br i1 %42, label %10, label %9, !llvm.loop !9
```

Optimizing Implementation 1, Cont'd

C

```
void update_positions(
    int nbodies,
    double *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    // …
    bodies[i] +=
      (bodies[i + 2] +
       new_velocity_x) *
      (time_quantum/2.0);
    bodies[i + 1] +=
      (bodies[i + 3] +
       new_velocity_y) *
      (time_quantum/2.0);
    // …
  }
}
```

LLVM IR

```
5:                                ; preds = %3
  …
  br label %10

10:                               ; preds = %5, %10
  …
  %24 = add nuw nsw i64 %11, 2
  %25 = getelementptr inbounds double,
    double* %1, i64 %24
  %26 = load double, double* %25, align 8
  %27 = fadd double %26, %19
  %28 = fdiv double %2, 2.000000e+00
  %29 = fmul double %28, %27
  …
  %32 = add nuw nsw i64 %11, 3
  %33 = getelementptr inbounds double,
    double* %1, i64 %32
  %34 = load double, double* %33, align 8
  %35 = fadd double %23, %34
  %36 = fdiv double %2, 2.000000e+00
  %37 = fmul double %36, %35
  …
  br i1 %42, label %10, label %9, !llvm.loop !9
```

%28

Eliminate the common subexpression!

Optimizing Implementation 1, Cont'd

C

```
void update_positions(
    int nbodies,
    double *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    // …
    bodies[i] +=
      (bodies[i + 2] +
       new_velocity_x) *
      (time_quantum/2.0);
    bodies[i + 1] +=
      (bodies[i + 3] +
       new_velocity_y) *
      (time_quantum/2.0);
    // …
  }
}
```

Replace with a cheaper operation!

LLVM IR

```
5:                                ; preds = %3
  …
  br label %10

10:                               ; preds = %5, %10
  …
  %24 = add nuw nsw i64 %11, 2
  %25 = getelementptr inbounds double,
    double* %1, i64 %24
  %26 = load double, double* %25, align 8
  %27 = fadd double %26, %19
  %28 = fdiv double %2, 2.000000e+00
  %29 = fmul double %28, %27
  …
  %32 = add nuw nsw i64 %11, 3
  %33 = getelementptr inbounds double,
    double* %1, i64 %32
  %34 = load double, double* %33, align 8
  %35 = fadd double %23, %34

  %36 = fmul double %28, %35
  …
  br i1 %42, label %10, label %9, !llvm.loop !9
```

%28 = fmul double %2, 5.000000e-01

Optimizing Implementation 1, Cont'd

C

```
void update_positions(
    int nbodies,
    double *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    // …
    bodies[i] +=
      (bodies[i + 2] +
       new_velocity_x) *
      (time_quantum/2.0);
    bodies[i + 1] +=
      (bodies[i + 3] +
       new_velocity_y) *
      (time_quantum/2.0);
    // …
  }
}
```

LLVM IR

```
5:                                ; preds = %3
  …
  br label %10

10:                               ; preds = %5, %10
  …
  %24 = add nuw nsw i64 %11, 2
  %25 = getelementptr inbounds double,
    double* %1, i64 %24
  %26 = load double, double* %25, align 8
  %27 = fadd double %26, %19
  %28 = fmul double %2, 5.000000e-01
  %29 = fmul double %28, %27
  …
  %32 = add nuw nsw i64 %11, 3
  %33 = getelementptr inbounds double,
    double* %1, i64 %32
  %34 = load double, double* %33, align 8
  %35 = fadd double %23, %34

  %36 = fmul double %28, %35
  …
  br i1 %42, label %10, label %9, !llvm.loop !9
```

Move loop-invariant code out of loop!

Optimizing Implementation 1, Cont'd: Result

C

```
void update_positions(
    int nbodies,
    double *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    // …
    bodies[i] +=
      (bodies[i + 2] +
       new_velocity_x) *
      (time_quantum/2.0);
    bodies[i + 1] +=
      (bodies[i + 3] +
       new_velocity_y) *
      (time_quantum/2.0);
    // …
  }
}
```

LLVM IR

```
5:                                ; preds = %3
  …
  %28 = fmul double %2, 5.000000e-01
  br label %10

10:                               ; preds = %5, %10
  …
  %24 = add nuw nsw i64 %11, 2
  %25 = getelementptr inbounds double,
    double* %1, i64 %24
  %26 = load double, double* %25, align 8
  %27 = fadd double %26, %19

  %29 = fmul double %28, %27
  …
  %32 = add nuw nsw i64 %11, 3
  %33 = getelementptr inbounds double,
    double* %1, i64 %32
  %34 = load double, double* %33, align 8
  %35 = fadd double %23, %34

  %36 = fmul double %28, %35
  …
  br i1 %42, label %10, label %9, !llvm.loop !9
```

Optimized Implementation 1

LLVM IR for loop body, `-O1` optimization

```
%12 = add nuw nsw i64 %11, 4
%13 = getelementptr inbounds double, double* %1, i64 %12
%14 = load double, double* %13, align 8
%15 = add nuw nsw i64 %11, 6
%16 = getelementptr inbounds double, double* %1, i64 %15
%17 = load double, double* %16, align 8
%18 = fdiv double %2, %17
%19 = fmul double %14, %18
%20 = add nuw nsw i64 %11, 5
%21 = getelementptr inbounds double, double* %1, i64 %20
%22 = load double, double* %21, align 8
%23 = fmul double %22, %18
%24 = add nuw nsw i64 %11, 2
%25 = getelementptr inbounds double, double* %1, i64 %24
%26 = load double, double* %25, align 8
%27 = fadd double %26, %19
%28 = fmul double %7, %27
%29 = getelementptr inbounds double, double* %1, i64 %11
%30 = load double, double* %29, align 8
%31 = fadd double %30, %28
store double %31, double* %29, align 8
%32 = add nuw nsw i64 %11, 3
%33 = getelementptr inbounds double, double* %1, i64 %32
%34 = load double, double* %33, align 8
%35 = fadd double %23, %34
%36 = fmul double %7, %35
%37 = add nuw nsw i64 %11, 1
%38 = getelementptr inbounds double, double* %1, i64 %37
%39 = load double, double* %38, align 8
%40 = fadd double %39, %36
store double %40, double* %38, align 8
store double %19, double* %25, align 8
store double %23, double* %33, align 8
```

Summary:

- 7 `loads`
- 1 `fdiv`
- 4 `fmul`
- 4 `fadd`
- 4 `stores`

Optimizing Structure Usage

N-Body Simulation Structures

Suppose we try cleaning up the code by introducing some higher-level structures.

2D vector

```
typedef struct vec_t {
  double x, y;
} vec_t;
```

Data structure for a body

```
typedef struct body_t {
  // Position vector
  vec_t position;
  // Velocity vector
  vec_t velocity;
  // Force vector
  vec_t force;
  // Mass
  double mass;
} body_t;
```

Implementation 2: Using Structures

```
void update_positions(int nbodies, body_t *bodies,
                      double time_quantum) {
  for (int i = 0; i < nbodies; ++i) {
    // Compute the new velocity of ith body.
    double new_velocity_x = bodies[i].force.x *
        (time_quantum / bodies[i].mass);
    double new_velocity_y = bodies[i].force.y *
        (time_quantum / bodies[i].mass);
    // Update the position of ith body based on
    // the average of its old and new velocity.
    bodies[i].position.x +=
        (bodies[i].velocity.x + new_velocity_x) *
        (time_quantum / 2.0);
    bodies[i].position.y +=
        (bodies[i].velocity.y + new_velocit
        (time_quantum / 2.0);
    // Set the new velocity of ith body.
    bodies[i].velocity.x = new_velocity_x;
    bodies[i].velocity.y = new_velocity_y;
  }
}
```

Our focus

Array indices have been replaced with accesses to structure members.

QUESTION: What does this abstraction cost in performance?

The `getelementptr` Instruction

The `getelementptr` instruction computes a memory address from a pointer and a list of indices.

C code

```
vec_t* A;
A[i].y;
```

Example: Compute the address `(%struct.vec_t* %0 + %1) + 1` using pointer arithmetic.

```
%3 = getelementptr inbounds %struct.vec_t,
     %struct.vec_t* %0, i64 %1, i32 1
```

Pointer to the memory for `A`

Index `i`

Field number of `y` in `vec_t`.

See `https://llvm.org/docs/GetElementPtr.html`

LLVM IR for Implementation 2

C

```
void update_positions(
    int nbodies,
    body_t *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    double new_velocity_x =
      bodies[i].force.x *
      (time_quantum /
       bodies[i].mass);
    // …
  }
}
```

LLVM IR

```
%18 = getelementptr inbounds %struct.body_t,
    %struct.body_t* %15, i64 %17
%19 = getelementptr inbounds %struct.body_t,
    %struct.body_t* %18, i32 0, i32 2
%20 = getelementptr inbounds %struct.vec_t,
    %struct.vec_t* %19, i32 0, i32 0
%21 = load double, double* %20, align 8
```

LLVM IR for Implementation 2

C

```
void update_positions(
    int nbodies,
    body_t *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    double new_velocity_x =
      bodies[i].force.x *
      (time_quantum /
       bodies[i].mass);
    // …
  }
}
```

Register %15 stores bodies and register %17 stores i.

LLVM IR

```
%18 = getelementptr inbounds %struct.body_t,
    %struct.body_t* %15, i64 %17
%19 = getelementptr inbounds %struct.body_t,
    %struct.body_t* %18, i32 0, i32 2
%20 = getelementptr inbounds %struct.vec_t,
                                 i32 0
                                 , align 8
```

Compute the address of the body_t at %15 + %17*sizeof(body_t).

LLVM IR for Implementation 2

C

```
void update_positions(
    int nbodies,
    body_t *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    double new_velocity_x =
      bodies[i].force.x *
      (time_quantum /
       bodies[i].mass);
    // …
  }
}
```

C

```
typedef struct body_t {
  // Position vector
  vec_t position;
  // Velocity vector
  vec_t velocity;
  // Force vector
  vec_t force;
  // Mass
  double mass;
} body_t;
```

LLVM IR

```
%18 = getelementptr inbounds %struct.body_t,
    %struct.body_t* %15, i64 %17
%19 = getelementptr inbounds %struct.body_t,
    %struct.body_t* %18, i32 0, i32 2
%20 = getelementptr inbounds %struct.vec_t,
```

Effect: Compute the address of field 2 in body_t at %18:
%18 + 0*sizeof(body_t) + 2*sizeof(vec_t).

LLVM IR for Implementation 2

C

```c
void update_positions(
    int nbodies,
    body_t *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    double new_velocity_x =
      bodies[i].force.x *
      (time_quantum /
       bodies[i].mass);
    // …
  }
}
```

C

```c
typedef struct vec_t {
  double x, y;
} vec_t;
```

Effect: Compute the address of field 0 in vec_t at %19:
%19 + 0*sizeof(vec_t) + 0*sizeof(double).

LLVM IR

```
%18 = getelementptr inbounds %struct.body_t,
    %struct.body_t* %15, i64 %17
%19 = getelementptr inbounds %struct.body_t,
    %struct.body_t* %18, i32 0, i32 2
%20 = getelementptr inbounds %struct.vec_t,
    %struct.vec_t* %19, i32 0, i32 0
%21 = load double, double* %20, align 8
```

LLVM IR for Implementation 2

C

```
void update_positions(
    int nbodies,
    body_t *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    double new_velocity_x =
      bodies[i].force.x *
      (time_quantum /
       bodies[i].mass);
    // …
  }
}
```

LLVM IR

```
%18 = getelementptr inbounds %struct.body_t,
    %struct.body_t* %15, i64 %17
%19 = getelementptr inbounds %struct.body_t,
    %struct.body_t* %18, i32 0, i32 2
%20 = getelementptr inbounds %struct.vec_t,
    %struct.vec_t* %19, i32 0, i32 0
%21 = load double, double* %20, align 8
```

Optimizing Implementation 2

C

```
void update_positions(
    int nbodies,
    body_t *bodies,
    double time_quantum) {
  for (int i = /* … */) {
    double new_velocity_x
      bodies[i].force.x *
      (time_quantum /
       bodies[i].mass);
    // …
  }
}
```

Simplify the arithmetic of the address calculation!

Effect: Compute the address at `%15 + %17*sizeof(body_t) + 2*sizeof(vec_t) + 0*sizeof(double)`.

LLVM IR

```
%18 = getelementptr inbounds %struct.body_t,
    %struct.body_t* %15, i64 %17
%19 = getelementptr inbounds %struct.body_t,
    %struct.body_t* %18, i32 0, i32 2
%20 = getelementptr inbounds %struct.vec_t,
    %struct.vec_t* %19, i32 0, i32 0
%21 = load double, double* %20, align 8
```

```
%20 = getelementptr inbounds %struct.body_t,
%struct.body_t* %15, i64 %17, i32 2, i32 0
```

Optimized Implementation 2

LLVM IR for loop body, -O1 optimization

```
%11 = getelementptr inbounds %struct.body_t, %struct.body_t* %1, i64 %10, i32 2, i32 0
%12 = load double, double* %11, align 8
%13 = getelementptr inbounds %struct.body_t, %struct.body_t* %1, i64 %10, i32 3
%14 = load double, double* %13, align 8
%15 = fdiv double %2, %14
%16 = fmul double %12, %15
%17 = getelementptr inbounds %struct.body_t, %struct.body_t* %1, i64 %10, i32
%18 = load double, double* %17, align 8
%19 = fmul double %18, %15
%20 = getelementptr inbounds %struct.body_t, %struct.body_t* %1, i64 %10, i32
%21 = load double, double* %20, align 8
%22 = fadd double %21, %16
%23 = fmul double %6, %22
%24 = getelementptr inbounds %struct.body_t, %struct.body_t* %1, i64 %10, i32
%25 = load double, double* %24, align 8
%26 = fadd double %25, %23
store double %26, double* %24, align 8
%27 = getelementptr inbounds %struct.body_t, %struct.body_t* %1, i64 %10, i32 1, i32 1
%28 = load double, double* %27, align 8
%29 = fadd double %19, %28
%30 = fmul double %6, %29
%31 = getelementptr inbounds %struct.body_t, %struct.body_t* %1,
%32 = load double, double* %31, align 8
%33 = fadd double %32, %30
store double %33, double* %31, align 8
store double %16, double* %20, align 8
store double %19, double* %27, align 8
```

Summary:

- 7 `load`s
- 1 `fdiv`
- 4 `fmul`
- 4 `fadd`
- 4 `store`s

Same as implementation 1!

Function Inlining

Basic Routines for 2D Vectors

Let's introduce a few simple routines to operate on 2D vectors.

```c
typedef struct vec_t {
  double x, y;
} vec_t;

static vec_t vec_add(vec_t a, vec_t b) {
  vec_t sum = { a.x + b.x, a.y + b.y };
  return sum;
}

static vec_t vec_scale(vec_t v, double a) {
  vec_t scaled = { v.x * a, v.y * a };
  return scaled;
}
```

Implementation 3: Function Calls

```
void update_positions(int nbodies, body_t *bodies,
                      double time_quantum) {
  for (int i = 0; i < nbodies; ++i) {
    // Compute the new velocity of
    vec_t new_velocity =
      vec_scale(bodies[i].force,
                time_quantum / bod
    // Update the position of ith
    // the average of its old and ne
    bodies[i].position =
      vec_add(bodies[i].position,
              vec_scale(vec_add(bodies[i].velocity,
                                new_velocity),
                        time_quantum / 2.0));
    // Set the new velocity of ith bo
    bodies[i].velocity = new_velocit
  }
}
```

This code expresses operations in terms of vectors instead of individual components.

Our focus

QUESTION: What does this abstraction cost in performance?

Example: Updating Positions

Let's see how the compiler optimizes function calls (after other optimizations).

C code from `update_positions`

```
vec_add(bodies[i].position,
        vec_scale(vec_add(bodies[i].velocity,
                          new_velocity),
                  time_quantum / 2.0));
```

Extract values from a `struct`-type LLVM IR register.

LLVM IR

```
%24 = extractvalue { double, double } %23, 0
%25 = extractvalue { double, double } %23, 1
%26 = fmul double %2, 5.000000e-01
%27 = call { double, double } @vec_scale(double %24,
    double %25, double %26)
```

Call `vec_scale`.

Function Inlining

LLVM IR snippet from `update_positions`

LLVM IR for `vec_scale`

```
define internal { double, double }
@vec_scale(double %0, double %1, doub
  %4 = fmul double %0, %2
  %5 = fmul double %1, %2
  %24 = extractvalue { double, double } %23, 0
  %25 = extractvalue { double, double } %23, 1
  %26 = fmul double %2, 5.000000e-01
  %27 = call { double, double } @vec_scale(double %24,
      double %25, double %26)
}
```

IDEA: The code for `vec_scale` is small, so copy-paste it into the call site.

Function Inlining

LLVM IR snippet from `update_positions`

```
%24 = extractvalue { double, double } %23, 0
%25 = extractvalue { double, double } %23, 1
%26 = fmul double %2, 5.000000e-01
%27 = call { double, double }
  @vec_scale(double %24, double %25, double %26)
%4.in = fmul double %24, %26
%5.in = fmul double %25, %26
%28 = insertvalue { double, double } undef, double %4.in, 0
%29 = insertvalue { double, double } %28, double %5.in, 1
ret { double, double } %29
```

Step 1: Copy code from `vec_scale`.

Step 2: Remove call and return.

Further Optimization

```
%24 = extractvalue { double, double } %23, 0
%25 = extractvalue { double, double } %23, 1
%26 = fmul double %2, 5.000000e-01


%4.in = fmul double %24, %26
%5.in = fmul double %25, %26
%28 = insertvalue { double, double } undef, double %4.in, 0
%29 = insertvalue { double, double } %28, double %5.in, 1
```

immediately unpack them.

```
%4.in = fmul double %24, %26
%5.in = fmul double %25, %26
%28 = insertvalue { double, double } undef, double %4.in, 0
%29 = insertvalue { double, double } %28, double %5.in, 1
%30 = extractvalue { double, double
%31 = extractvalue { double, double
```

IDEA: Remove these useless operations.

Sequences of Function Calls

C code

```
vec_add(bodies[i].position,
        vec_scale(vec_add(bodies[i].velocity,
                          new_velocity),
                  time_quantum / 2.0));
```

LLVM IR

```
%23 = call { double, double } @vec_add(double %20,
      double %22, double %17, double %18)
%24 = extractvalue { double, double } %23, 0
%25 = extractvalue { double, double } %2
%26 = fmul double %2, 5.000000e-01
%4.in = fmul double %24, %26
%5.in = fmul double %25, %26
…
%34 = call { double, double } @vec_
      double %33, double %4.in, dou
```

IDEA: Inline `vec_add` as well.

…and then remove useless instructions…

Sequences of Function Calls

C code

```
vec_add(bodies[i].position,
        vec_scale(vec_add(bodies[i].velocity,
                          new_velocity),
                  time_quantum / 2.0));
```

Optimized LLVM IR

```
%22 = fadd double %19, %16
%23 = fadd double %21, %17
%26 = fmul double %2, 5.000000e-01
%4.in = fmul double %22, %26
%5.in = fmul double %23, %26
…
%31 = fadd double %28, %4.in
%32 = fadd double %30, %5.in
```

SUMMARY: Function inlining and additional transformations can eliminate the cost of the function abstraction.

LLVM IR for Implementation 3

Optimized LLVM IR for loop body (without vectorization)

```
%11 = getelementptr inbounds %struct.body_t, %struct.body_t* %1, i64 %10, i32 3
%12 = load double, double* %11, align 8
%13 = fdiv double %2, %12
%14 = getelementptr inbounds %struct.body_t, %struct.body_t* %1, i64 %10, i32
%15 = load double, double* %14, align 8
%16 = getelementptr inbounds %struct.body_t, %struct.body_t* %1, i64 %10, i32
%17 = load double, double* %16, align 8
%18 = fmul double %15, %13
%19 = fmul double %13, %17
%20 = getelementptr inbounds %struct.body_t, %struct.body_t* %1, i64 %10, i32
%21 = load double, double* %20, align 8
%22 = getelementptr inbounds %struct.body_t, %struct.body_t* %1, i64 %10, i32
%23 = load double, double* %22, align 8
%24 = fadd double %18, %21
%25 = fadd double %19, %23
%26 = fmul double %6, %24
%27 = fmul double %6, %25
%28 = getelementptr inbounds %struct.body_t, %struct.body_t* %1, i64 %10, i32 0, i32 0
%29 = load double, double* %28, align 8
%30 = getelementptr inbounds %struct.body_t, %struct.body_t* %1, i64 %
%31 = load double, double* %30, align 8
%32 = fadd double %29, %26
%33 = fadd double %31, %27
store double %32, double* %28, align 8
store double %33, double* %30, align 8
store double %18, double* %20, align 8
store double %19, double* %22, align 8
```

Summary:

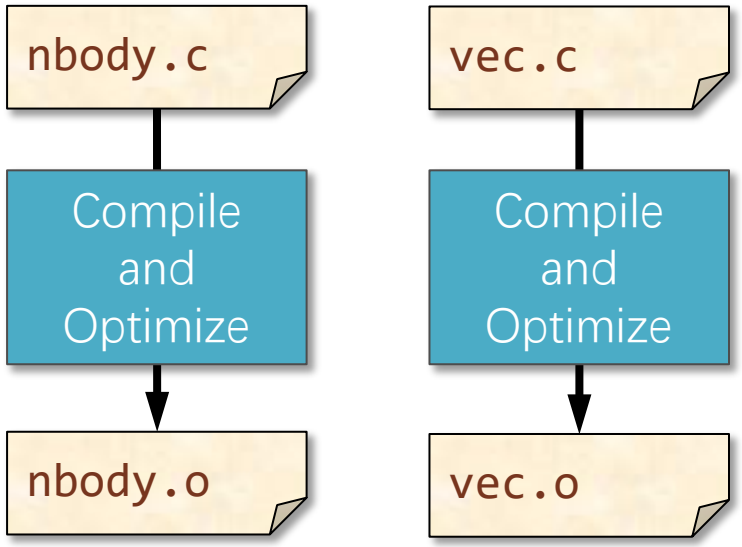
- 7 `load`s
- 1 `fdiv`
- 4 `fmul`
- 4 `fadd`
- 4 `store`s

Same as implementations 1 and 2!

Problems with Function Inlining

Why doesn't the compiler inline all function calls?

- Some function calls, such as recursive calls, cannot be inlined except in special cases, e.g., "recursive tail calls."
- The compiler cannot inline a function defined in another **compilation unit** unless one uses **whole-program optimization**.



- Function inlining can increase code size, which can hurt performance.

Controlling Function Inlining

QUESTION: How does the compiler know whether or not inlining a function will hurt performance?

ANSWER: It doesn't know. It makes a best guess based on heuristics, such as the function's size.

Tips for controlling function inlining:

- Mark functions that should always be inlined with `__attribute__((always_inline))`.
- Mark functions that should never be inlined with `__attribute__((noinline))`.
- Use **link-time optimization (LTO)** to enable whole-program optimization.

Assembly-Level Optimizations

Arithmetic Opt's: C vs. LLVM IR

Many compiler optimizations happen on the compiler's **intermediate representation (IR)**, although not all of them.

EXAMPLES: Let `n` be a `uint32_t`.

Register `%0` holds the value of `n`.

C code	LLVM IR
`uint32_t x = n * 8;`	`%2 = shl nsw i32 %0, 3`
`uint32_t y = n * 15;`	`%3 = mul nsw i32 %0, 15`
`uint32_t z = n / 71;`	`%4 = udiv i32 %0, 71`

Arithmetic Opt's: C vs. Assembly

Most compiler optimizations happen on the compiler's **intermediate representation (IR)**, although not all of them.

EXAMPLES: Let `n` be a `uint32_t`.

Register `%rdi` holds the value of `n`.

C code

```
uint32_t x = n * 8;
```

Assembly

```
leal   (,%rdi,8), %eax
```

```
uint32_t y = n * 15;
```

```
leal   (%rdi,%rdi,4), %eax
leal   (%rax,%rax,2), %eax
```

```
uint32_t z = n / 71;
```

Magic number equal to $2^{38}/71+1$.

```
movl   %edi, %eax
movl   $3871519817, %ecx
imulq  %rax, %rcx
shrq   $38, %rcx
```

Other Assembly-Level Opt's

Compilers perform a variety of optimizations at the assembly level, including the following:

- **Register allocation:** Choose which architecture registers will store different values at different points in time.
- **Instruction reordering:** Order assembly instructions to effectively use the specific processor pipeline.
- Standard compiler optimizations — such as loop-invariant-code motion or common-subexpression elimination — on instructions that emerge only at the assembly level.

Case Study 1

Implementation 4: System Pointer

Suppose that we modify the n-body simulation code to encapsulate all of the arguments to `update_positions` into a single data structure.

Data structure for the system

```
typedef struct system_t {
  // Number of bodies
  int nbodies;
  // Array of bodies
  body_t *bodies;
  // Time quantum
  double time_quantum;
} system_t;
```

Implementation 4: System Pointer

```
void update_positions(system_t *sys) {
  for (int i = 0; i < sys->nbodies; ++
    // Compute the new velocity of ith
    vec_t new_velocity =
      vec_scale(sys->bodies[i].force,
                sys->time_quantum / sys->bodies[i].mass);
    // Update the position of ith body based on
    // the average of its old and new velocity.
    sys->bodies[i].position =
      vec_add(sys->bodies[i].position,
              vec_scale(vec_add(sys->bodies[i].velocity,
                                new_velocity),
                        sys->time_quantum / 2.0));
    // Set the new velocity of ith body.
    sys->bodies[i].velocity = new_
  }
}
```

Accesses to `nbodies`, `time_quantum`, and `bodies` go through the `sys` pointer.

QUESTION: What does this abstraction cost in performance?

LLVM IR for Implementation 4

LLVM IR for loop body, -O1 optimization

```
%11 = load %struct.body_t*, %struct.body_t** %6, align 8
%12 = load double, double* %7, align 8
%18 = getelementptr inbounds %struct.body_t, %st
%19 = load double, double* %18, align 8
%20 = fmul double %17, %15
%21 = fmul double %15, %19
%22 = getelementptr inbounds %struct.body_t, %st
%23 = load double, double* %22, align 8
%27 = fadd double %21, %25
%28 = fmul double %12, 5.000000e-01
```

Reload bodies and time_quantum.

Recompute time_quantum/2.0.

```
%37 = load %struct.body_t*, %struct.body_t** %6, align 8
%38 = getelementptr inbounds %struct.body_t, %struct.body_t* %37,
    i64 %10, i32 1, i32 0
store double %20, double* %38, align 8
%39 = getelementptr inbounds %struct.body_t, %struct.body_t* %37,
    i64 %10, i32 1, i32 1
store double %21, double* %39, align 8
%41 = load i32, i32* %2, align 8
%42 = sext i32 %41 to i64
```

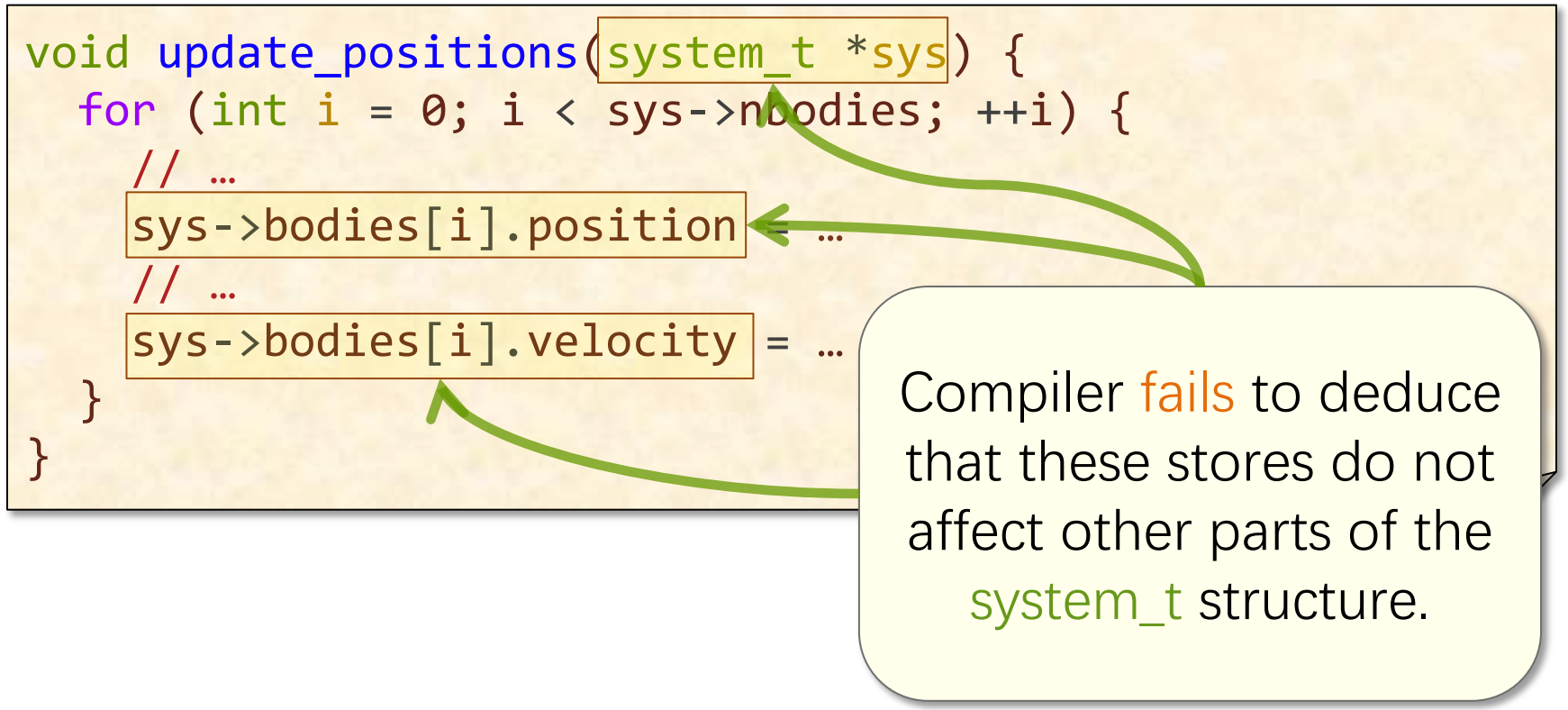
Reload bodies and nbodies.

Summary:

- 11 loads
- 1 fdiv
- 5 fmul
- 4 fadd
- 4 stores

What Went Wrong

PROBLEM: The stores in the function cause the compiler to act conservatively, because it is unsure about potential memory aliasing.



What Went Wrong, Cont'd

```
void update_positions(system_t *sys) {
  for (int i = 0; i < sys->nbodies; ++i) {
    // Compute the new velocity of body.
    vec_t new_velocity =
      vec_scale(sys->bodies[i].force,
                sys->time_quantum / sys->bodies[i].mass);
                                  of body
                                  old and
                                  n =
                                  i].positi
                vec_scale(vec_add(sys->bodies[i].velocity,
                                  new_velocity),
                          sys->time_quantum / 2.0));
    // Set the new velocity of body.
    sys->bodies[i].velocity = new_velocity;
  }
}
```

Compiler isn't sure that previous stores won't modify these values!

Compiler can't prove that this value is loop-invariant.

Fundamental Problem: Alias Analysis

ALIAS-ANALYSIS PROBLEM: Given two pointers in a program, determine statically — by studying the code itself — if they can **alias** — point to the same memory location.

- BAD NEWS: This problem is **undecidable**, meaning no compiler can solve it in general.
- In practice, compilers try to solve common, special instances of this problem, by analyzing the program's control flow, data types, programmer annotations — e.g., `const`, `restrict` — and more.
- Improvements to alias analysis make compiler optimizations a moving target.

Implementation 5: Globals

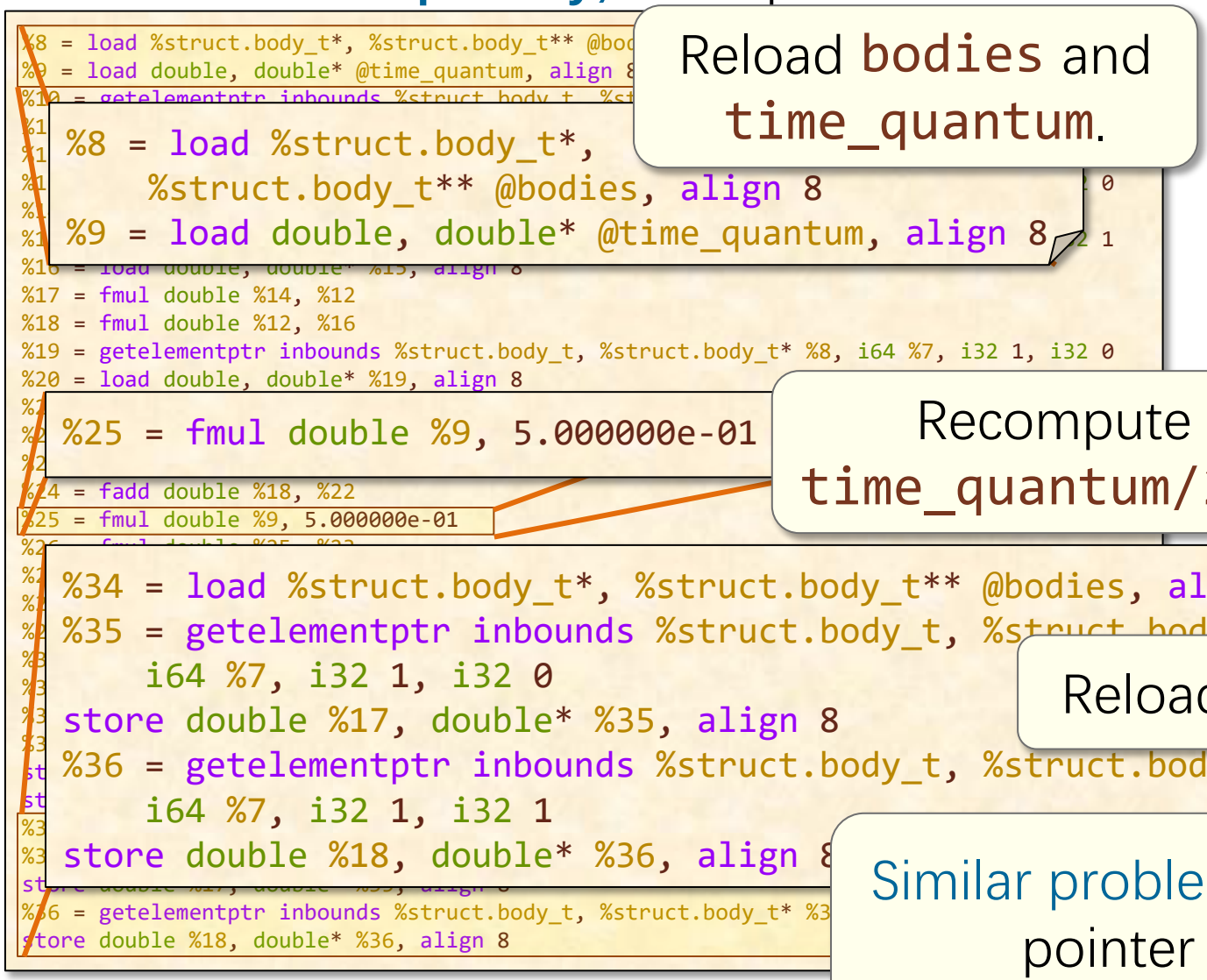
```
int nbodies;
body_t *bodies;
double time_quantum;
void update_positions() {
  for (int i = 0; i < nbodies; ++i) {
    // Compute the new velocity of body.
    vec_t new_velocity =
      vec_scale(bodies[i].force,
                time_quantum / bodies[i].mass);
    // Update the position of body based on
    // the average of its old and new velocity.
    bodies[i].position =
      vec_add(bodies[i].position,
              vec_scale(vec_add(bodies[i].velocity,
                                new_velocity),
                        time_quantum / 2.0));
    // Set the new velocity of body.
    bodies[i].velocity = new_velocity
  }
}
```

The `nbodies`, `time_quantum`, and `bodies` variables reside in global memory.

QUESTION: What does this change cost in performance?

LLVM IR for Implementation 5

LLVM IR for loop body, -O1 optimization



Reload `bodies` and `time_quantum`.

Recompute `time_quantum/2.0`.

Reload `bodies`.

Similar problems to system-pointer version!

Summary:

- 10 `loads`
- 1 `fdiv`
- 5 `fmul`
- 4 `fadd`
- 4 `stores`

Take-Aways

The compiler must optimize code that uses multiple pointers conservatively, in case those pointers alias.

- Although compilers may improve their alias analysis over time, there will always be deficiencies.
- Global data can also trigger alias-analysis problems for the compiler.
- In some cases, the compiler will optimize code by generating runtime checks for memory aliasing. (See homework 3.)
- TIP: Use qualifiers (e.g., `const`, `restrict`) and local variables to help the compiler out.

Case Study 2

Example: Simple Accesses

Compilers effectively optimize memory accesses based on simple integer offsets.

QUESTION: Does the compiler vectorize this code?

C

```
void foo(int *A, int n) {
  for (int i = 0; i < n; ++i)
    A[i]++;
}
```

LLVM IR

```
…
%19 = getelementptr inbounds i32, i32* %0, i64 %17
%20 = bitcast i32* %19 to <4 x i32>*
%21 = load <4 x i32>, <4 x i32>* %20, align 4
%22 = getelementptr inbounds i32, i32* %19, i64 4
%23 = bitcast i32* %22 to <4 x i32>*
%24 = load <4 x i32>, <4 x i32>* %23, align 4
%25 = add nsw <4 x i32> %21, <i32 1, i32 1, i32 1, i32 1>
%26 = add nsw <4 x i32> %24, <i32 1, i32 1, i32 1, i32 1>
store <4 x i32> %25, <4 x i32>* %20, align 4
store <4 x i32> %26, <4 x i32>* %23, align 4
…
```

Yes.

Example: Indirect Accesses

QUESTION: Does the compiler vectorize this code?

C

```
void foo(int *restrict A,
         const int *restrict B, int n) {
  for (int i = 0; i < n; ++i)
    A[B[i]]++;
}
```

LLVM IR

```
…
%31 = getelementptr inbounds i32, i32* %1, i64 %29
%32 = load i32, i32* %31, align 4
%33 = sext i32 %32 to i64
%34 = getelementptr inbounds i32, i32* %0, i64 %33
%35 = load i32, i32* %34, align 4
%36 = add nsw i32 %35, 1
store i32 %36, i32* %34, align 4
…
```

No.

Fundamental Problem: Indirect Accesses

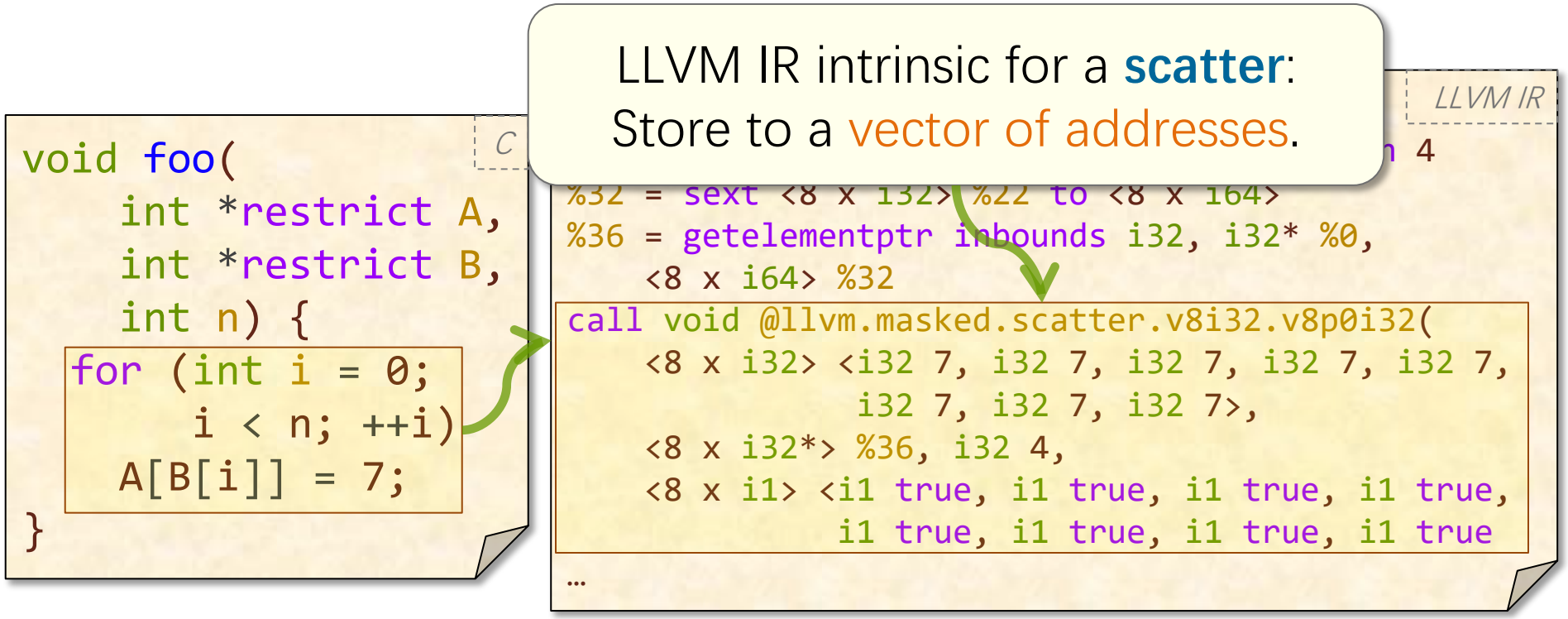
PROBLEM: Compilers have a hard time optimizing **indirect memory accesses**, where the memory location accessed is itself read from memory.

The accesses into A might not be known until runtime.

```
void foo(int *restrict A,
         const int *restrict B,
         int n) {
  for (int i = 0; i < n; ++i)
    A[B[i]]++;
}
```

Vector Scatter and Gather

Sometimes, compilers can use gather and scatter instructions to vectorize indirect accesses.



Using these instructions depends on the available hardware, the code, and the costs of different operations.

Optimizing Local Variables

A compiler can optimize indirect memory accesses when it can statically analyze the indirection.

C

```
void foo(int *A) {
  int B[4] = {2, 0, 1, 3};
  for (int i = 0; i < 4; ++i)
    A[B[i]]++;
}
```

The small loop is fully unrolled, enabling further optimizations.

LLVM IR

```
define void @foo(i32* nocapture noundef %0) {
  %2 = bitcast i32* %0 to <4 x i32>*
  %3 = load <4 x i32>, <4 x i32>* %2, align 4
  %4 = add nsw <4 x i32> %3, <i32 1, i32 1, i32 1, i32 1>
  store <4 x i32> %4, <4 x i32>* %2, align 4
  ret void
}
```

Optimizing Local `malloc`'d Variables

Compilers can perform such optimizations even when local variables are allocated using `malloc`.

C

```
void foo(int *A) {
  int *B = (int *)malloc(sizeof(int) * 4);
  B[0] = 2; B[1] = 0; B[2] = 1; B[3] = 3;
  for (int i = 0; i < 4; ++i)
    A[B[i]]++;
  free(B);
}
```

The compiler treats `malloc` specially for alias analysis.

LLVM IR

```
define void @foo(i32* nocapture noundef %0) {
  %2 = bitcast i32* %0 to <4 x i32>*
  %3 = load <4 x i32>, <4 x i32>* %2, align 4
  %4 = add nsw <4 x i32> %3, <i32 1, i32 1, i32 1, i32 1>
  store <4 x i32> %4, <4 x i32>* %2, align 4
  ret void
}
```

Optimization Failure With Locals

But compilers can still fail to optimize indirect accesses even when they have perfect information.

C

```
void foo(int *A, int n) {
  int *B = (int *)malloc(sizeof(int) * n);
  for (int i = 0; i < n; ++i)
    B[i] = i;
  for (int i = 0; i < n; ++i)
    A[B[i]]++;
  free(B);
}
```

The compiler fails to recognize that `B[i]` is the identity function.

LLVM IR

```
…
%32 = load i32, i32* %31, align 4
%33 = sext i32 %32 to i64
%34 = getelementptr inbounds i32, i32* %0, i64 %33
%35 = load i32, i32* %34, align 4
%36 = add nsw i32 %35, 1
store i32 %36, i32* %34, align 4
…
```

Take-Aways

The compiler may struggle to optimize indirect memory accesses.

- Such indirect memory accesses may be input dependent, which substantially limits what the compiler can do.
- Existing compiler limitations may prevent optimization of indirect accesses.
- Compilers are better able to optimize local variables than nonlocal variables.
- Check the LLVM IR or assembly to verify whether the compiler did the optimizations you want.

SUMMARY

Summary: What the Compiler Does

Compilers transform code through a sequence of **transformation passes**.

- The compiler knows a set of transformations, many of which resemble Bentley-rule work optimizations.
- The compiler repeatedly goes over the code and mechanically applies these transformations.
- One transformation can enable other transformations.

Compilers perform many more transformations than those shown in this lecture.

Summary: What Stops The Compiler?

Compiler generated code must be correct in all cases, including:

- For any given input, and
- For any variation of the architectures.

Compilers are conservative, often use heuristics, and must assume the worst of:

- Memory aliasing
- Indirect accesses
- Cost model

Use compiler flags, annotations and simple code rewrites to trigger the optimizations.

Want to Improve the Compiler?

You can also try modifying the compiler itself to overcome some of its current limitations!

SHAMELESS PLUG: If you're interested in UROP or MEng projects related to compilers, come talk to me!