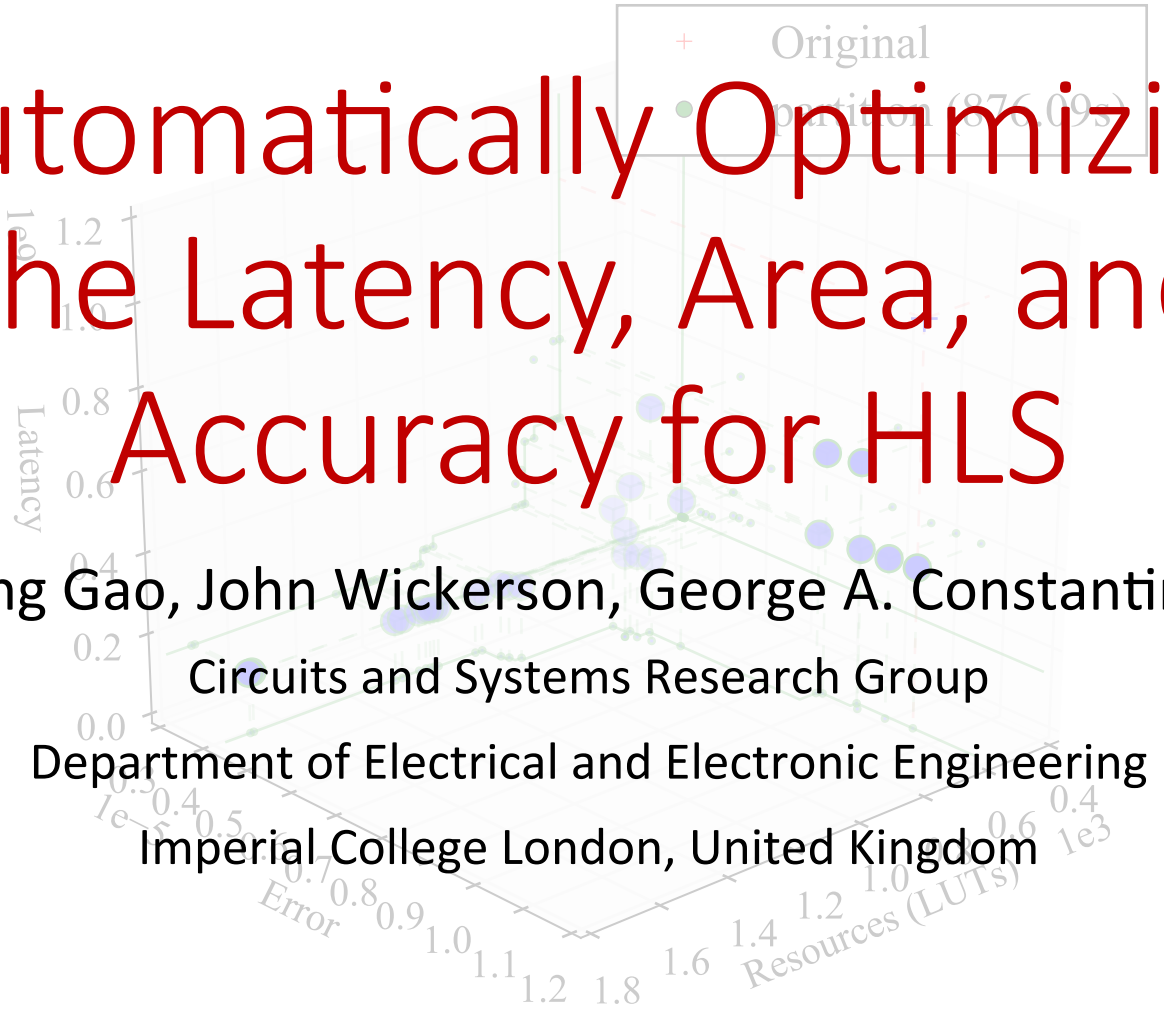
Imperial College London

Automatically Optimizing the Latency, Area, and Accuracy for HLS



Xitong Gao, John Wickerson, George A. Constantinides

Circuits and Systems Research Group

Department of Electrical and Electronic Engineering

Imperial College London, United Kingdom

Numerical Programs on FPGAs

Present

- RTL implementations
- Error-prone
- Slow to develop
- High development costs

Future

- Synthesize C programs with HLS
- Easy to debug & verify
- Comparable performance
- Design space exploration

Numerical Programs

- Often consist of floating-point computations
  - Long latency
  - A lot of resources
- Often spend most of their time in loops
  - Loop pipelining

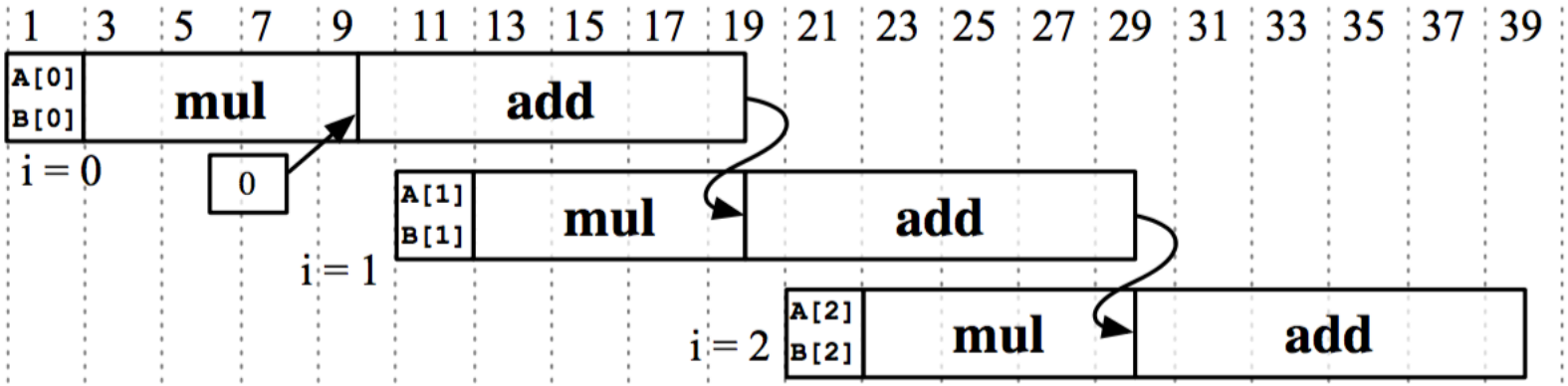
Motivating Example

Dot product:

```
float d = 0.0f;
for (int i = 0; i < 1024; i++)
    d = d + A[i] * B[i];
```

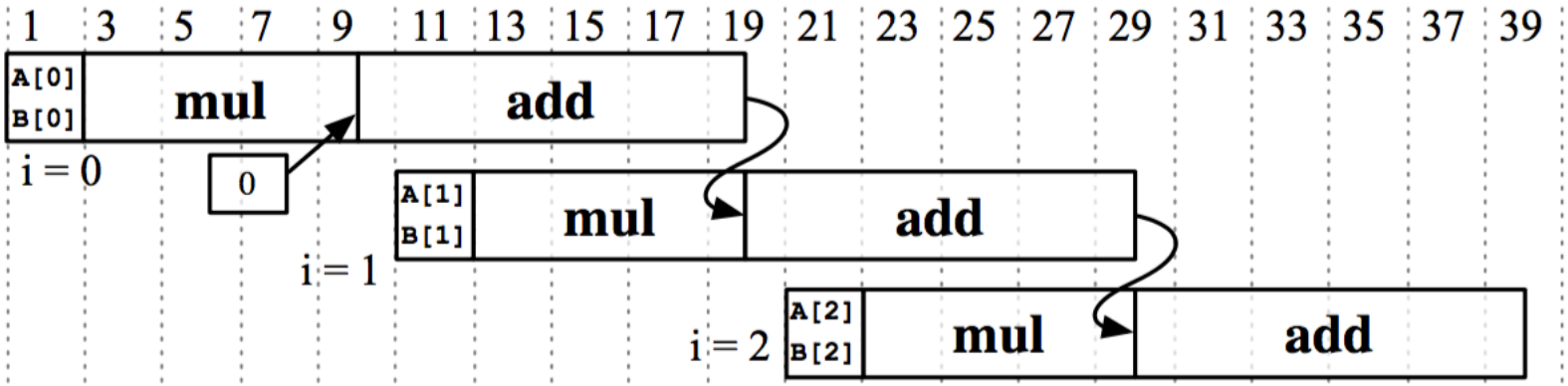
Motivating Example

```
float d = 0.0f;
for (int i = 0; i < 1024; i++)
    d = d + A[i] * B[i];
```



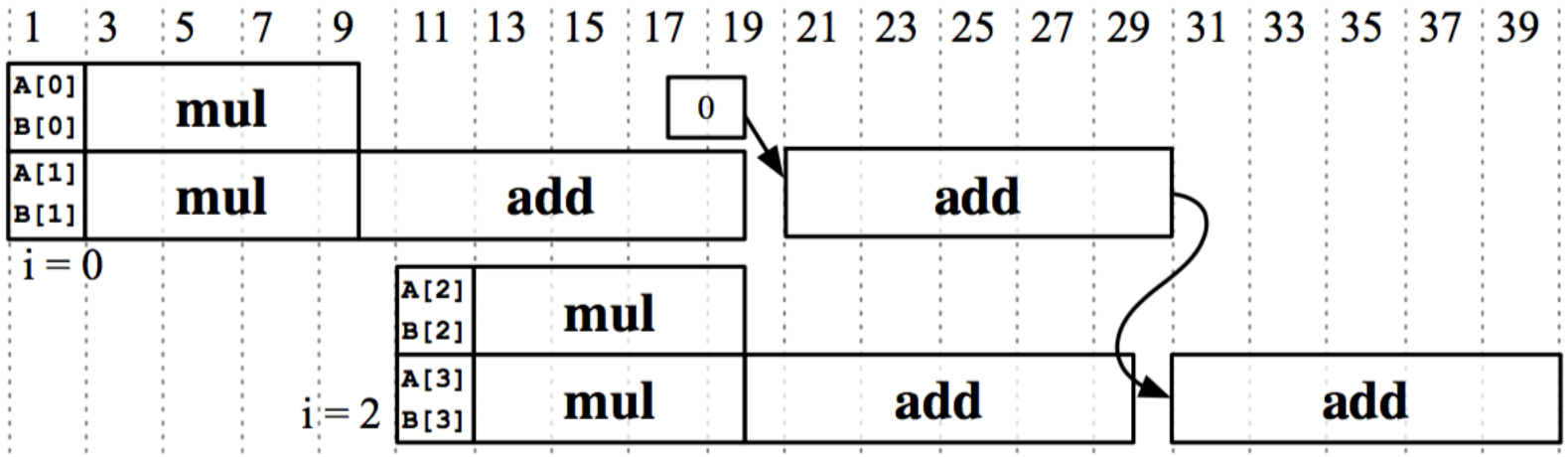
Motivating Example

```
float d = 0.0f;
for (int i = 0; i < 1024; i += 2) {
    d = d + A[i]*B[i];
    d = d + A[i+1]*B[i+1];
}
```



Motivating Example

```
float d = 0.0f;
for (int i = 0; i < 1024; i += 2)
    d = d + (A[i]*B[i] + A[i+1]*B[i+1]);
```



Problems with Arithmetic Equivalences

Single-precision floating-point:

$((1 + 2^{-24}) + 2^{-24}) - 1$

$(1 + (2^{-24} + 2^{-24})) - 1$

Problems with Arithmetic Equivalences

Single-precision floating-point:

$((1 + 2^{-24}) + 2^{-24}) - 1 = 0$ Round-off Error: 2^{-23}

$(1 + (2^{-24} + 2^{-24})) - 1 = 0.00000012...$

Round-off Error: 0

Problems with Arithmetic Equivalences

Many of the arithmetic rules do not hold under floating-point arithmetic:

- **Associativity**: `(a + b) + c ≠ a + (b + c)`
- **Distributivity**: `a*(b + c) ≠ a*b + a*c`
- **Square diff.**: $a^2 - b^2 \neq (a + b) * (a - b)$
- Many more…

Problems with Arithmetic Equivalences

HLS tools (such as **LegUp** and **Vivado HLS**) have limited use of them and do not use them by default.

`-funsafe-math-optimizations`

Can we use them to our advantage safely?

Round-off Errors: Equivalence?

SOAP3:

Automatically and **simultaneously** optimizes **latency**, **resources**, and **accuracy** of numerical programs by exploiting arithmetic rules and many more for HLS.

Learn to use SOAP in 10 Seconds

```
#define N 1000
#define TSTEPS 20
```

```
for (int t = 0; t < TSTEPS; t++)
  for (int i = 1; i < N - 1; i++)
    for (int j = 1; j < N - 1; j++)
      A[i][j] = (
        A[i-1][j] + A[i][j-1] + A[i][j] +
        A[i][j+1] + A[i+1][j]
      ) * 0.2f;
```

Learn to use SOAP in 10 Seconds

```
#define N 1000
#define TSTEPS 20

#pragma soap input \
        float A[N][N] = [0.0, 1.0]
#pragma soap output A

for (int t = 0; t < TSTEPS; t++)
  for (int i = 1; i < N - 1; i++)
    for (int j = 1; j < N - 1; j++)
      A[i][j] = (
        A[i-1][j] + A[i][j-1] + A[i][j] +
        A[i][j+1] + A[i+1][j]
      ) * 0.2f;
```

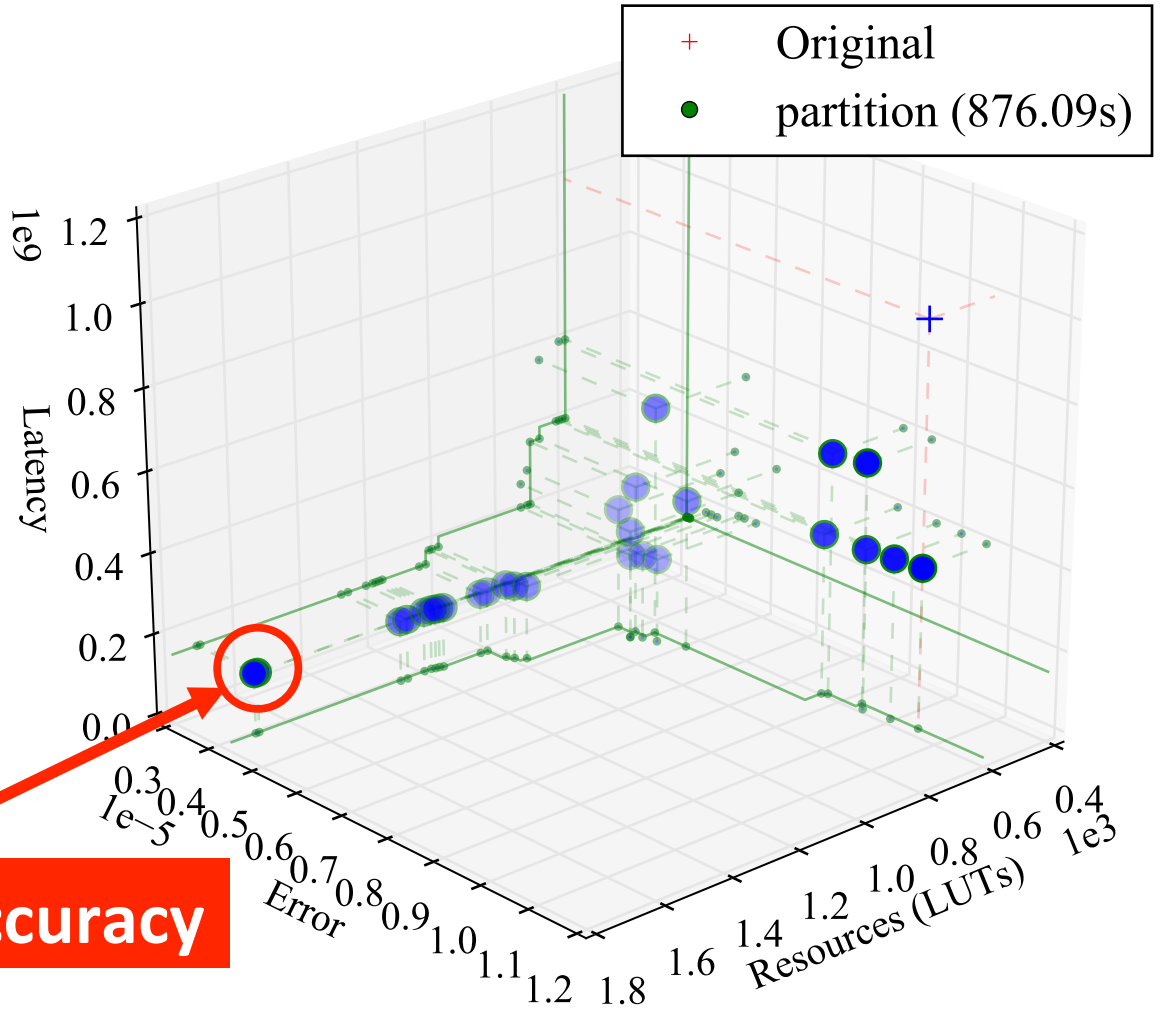
Add this

Push one button…

Wait a few minutes…

This is what you get

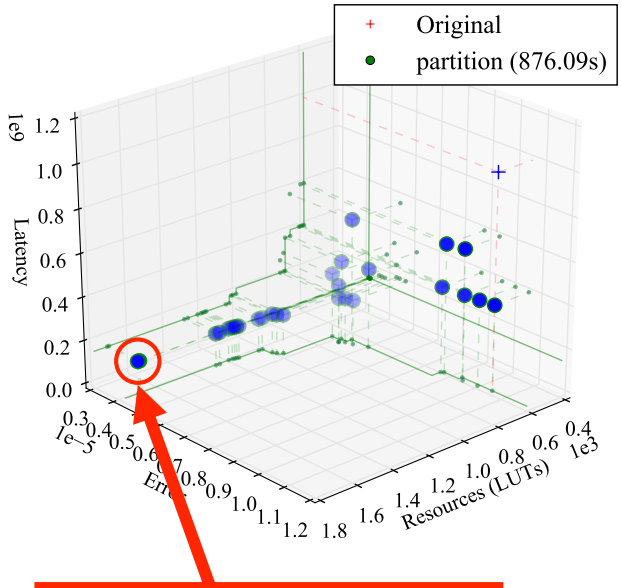
- Explores a huge number of equivalent programs.
- Produces a set of optimized programs - 3D Pareto frontier.



Best latency and accuracy

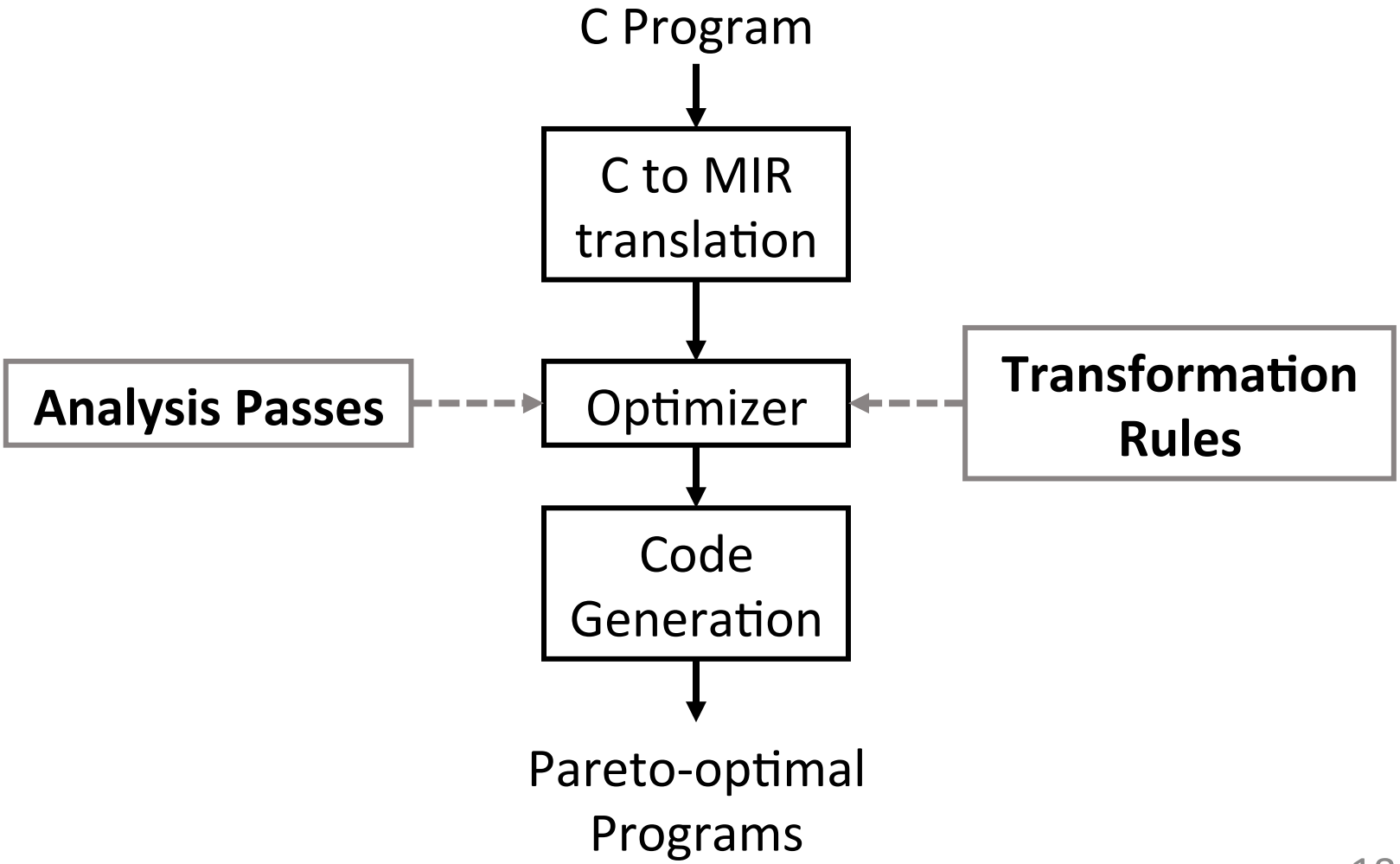
Comparison

- Optimizing the example code for latency and accuracy:

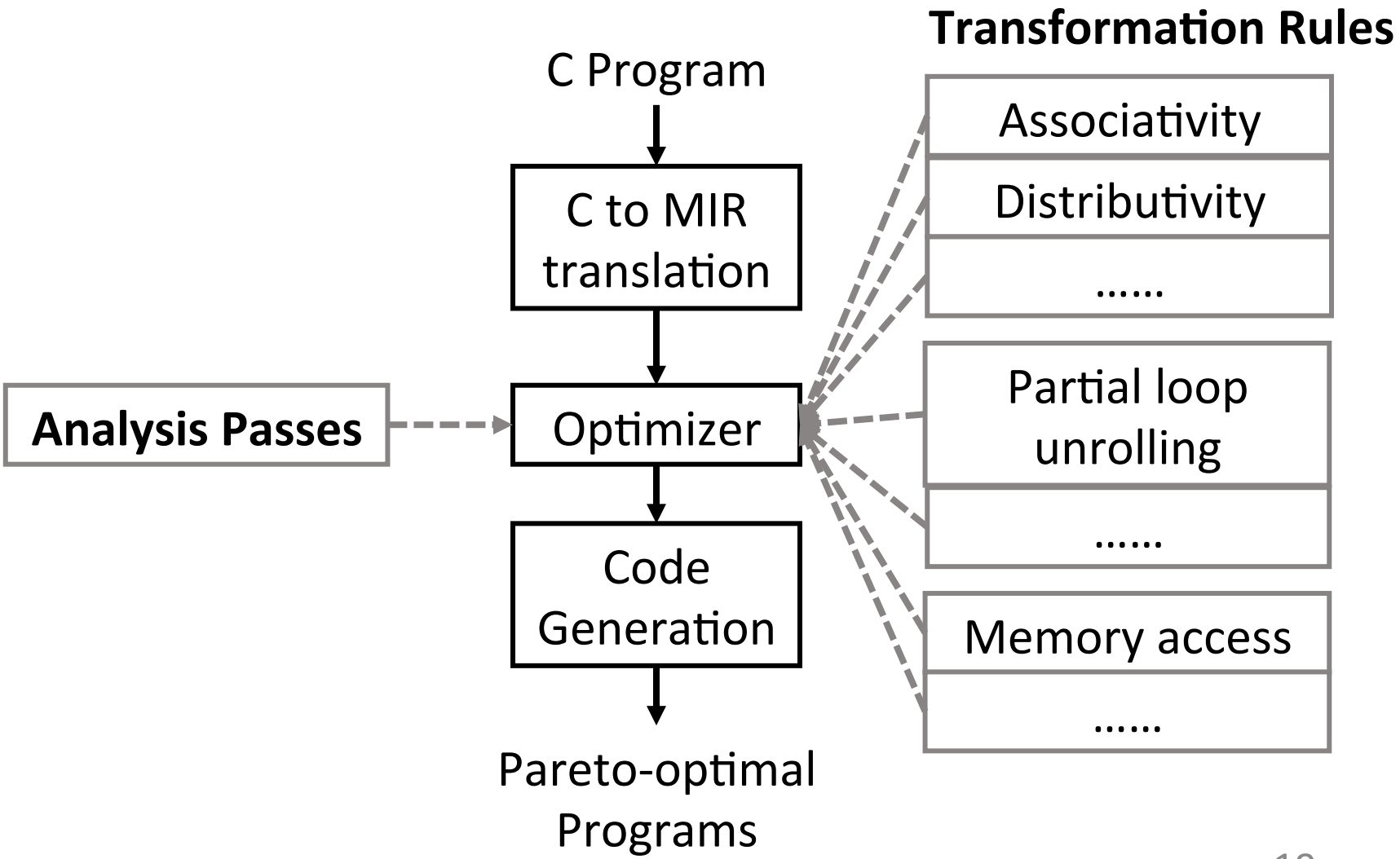


Improvements	Vivado HLS (Expression Balance)	SOAP + VHLS
Run time (s)	1.2x	7.0x
Resources (LUTs)	1.3x	3.5x
Accuracy (Worst-case error)	???????	2.5x

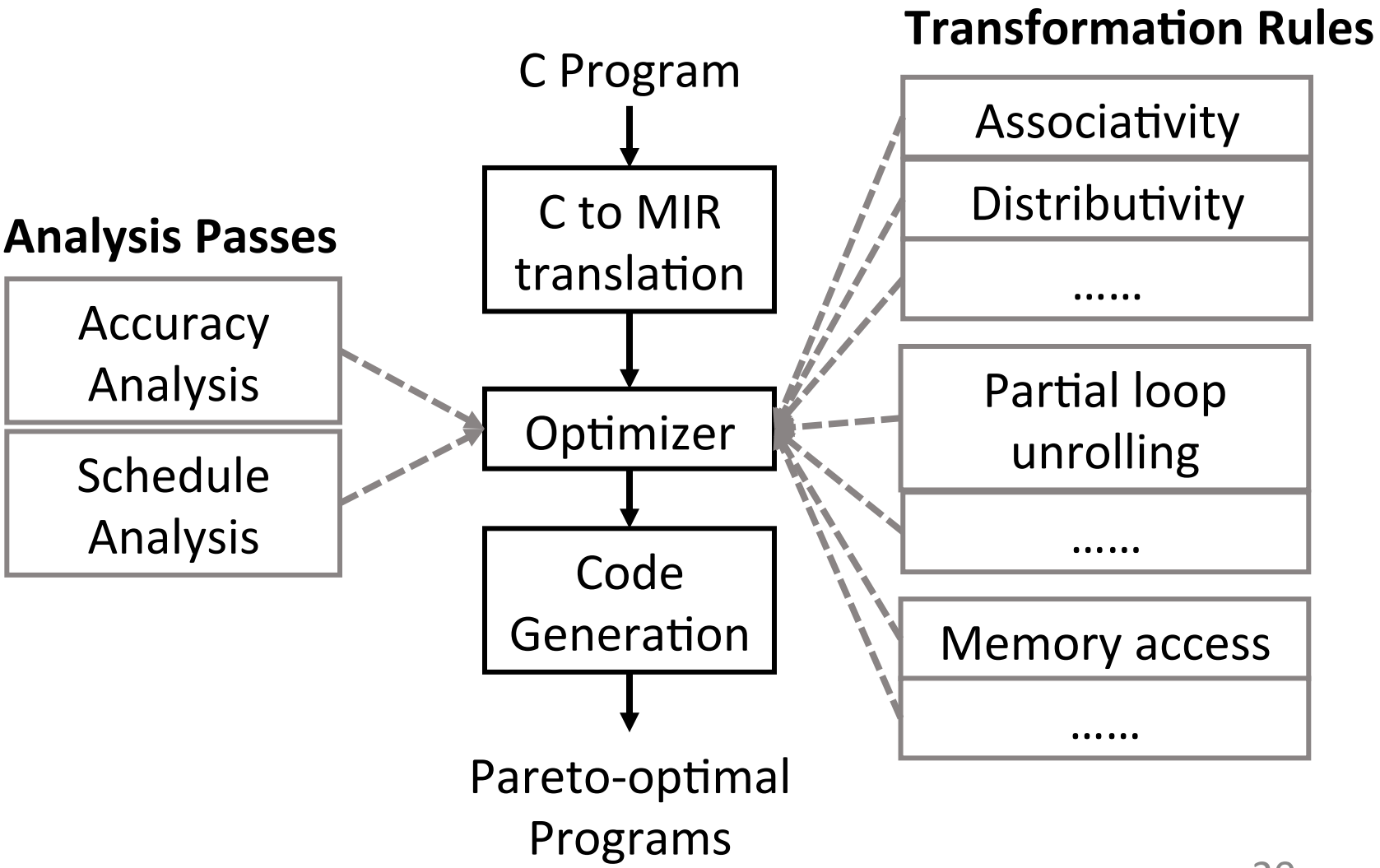
Tool flow


C Program
C to MIR translation
Analysis Passes
Optimizer
Transformation Rules
Code Generation
Pareto-optimal Programs

Tool flow


Transformation Rules
C Program
C to MIR translation
Analysis Passes
Optimizer
Code Generation
Pareto-optimal Programs
Associativity
Distributivity
……
Partial loop unrolling
……
Memory access
……

Tool flow


Transformation Rules
C Program
Associativity
Distributivity
.....
C to MIR translation
Analysis Passes
Accuracy Analysis
Schedule Analysis
Optimizer
Partial loop unrolling
.....
Code Generation
Memory access
.....
Pareto-optimal Programs

MIR: Yet another IR?

- An expression-like IR that specifically tackles the functional equivalence of numerical programs
  - – ***how*** a program is executed
  - + ***effect of executing*** the program
- Greatly reduces the size of search space, but optimal solutions are kept

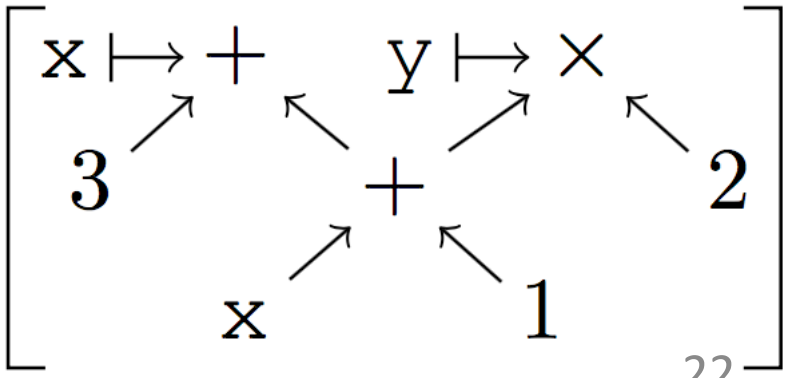
MIR: Straight-line code

```
y = x + 1;
x = y;
y = y * 2;
x = x + 3;
```

```
x = x + 1;
y = 2 * x;
x = x + 3;
```

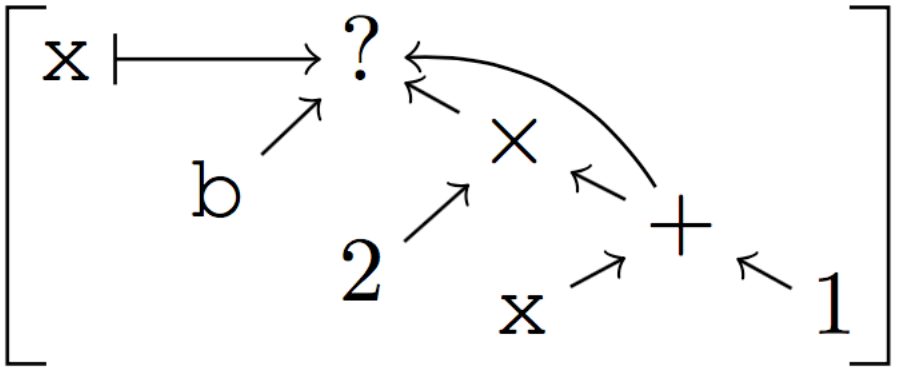
.....

Infinitely many equivalent programs…



MIR: Conditionals

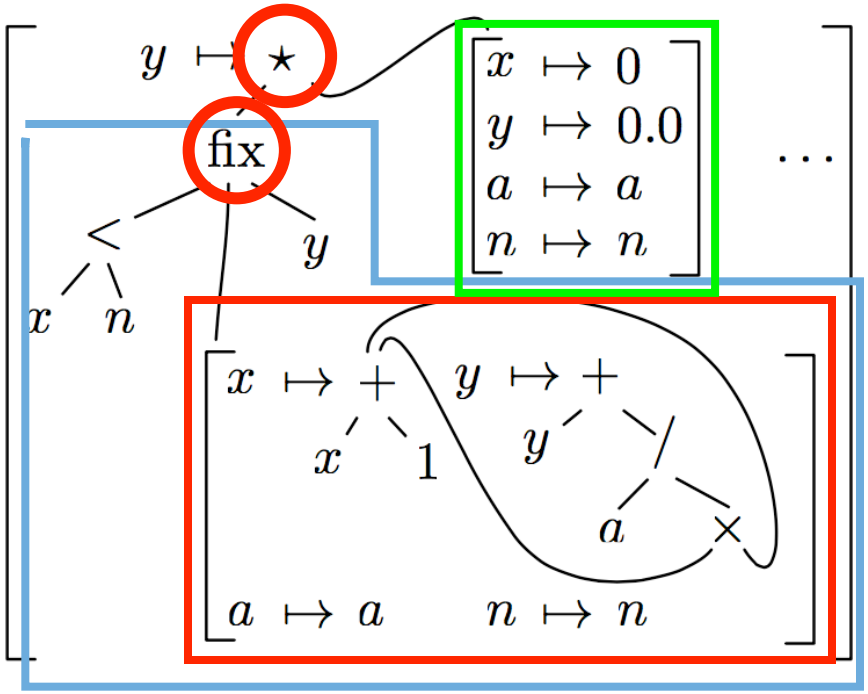
```
x = x + 1;
if (b) {
    x = 2 * x;
}
```



MIR: Loops

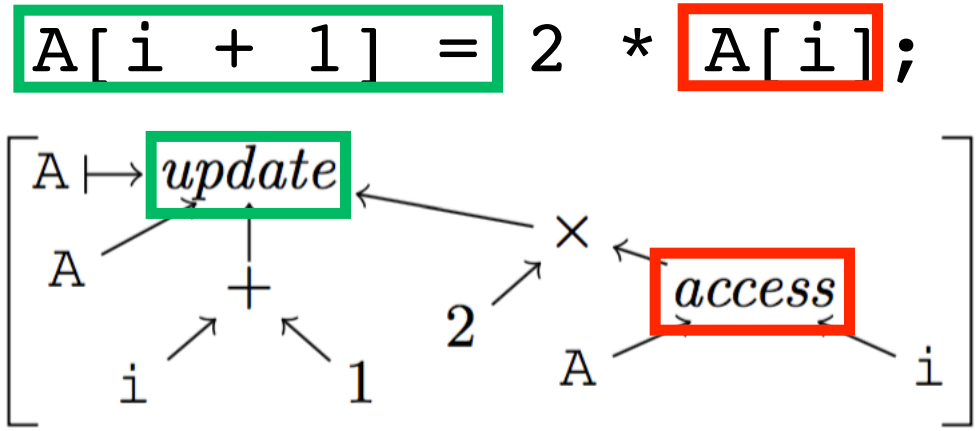
- Loops are infinite depth expressions with recurring structure.

```
x = 0;
y = 0.0f;
while (x < n) {
    x = x + 1;
    y = y + a /
        (x * x);
}
```



MIR: Array accesses

- In our MIR, we capture the read and write operations with *update* and *access* operators respectively.



Results

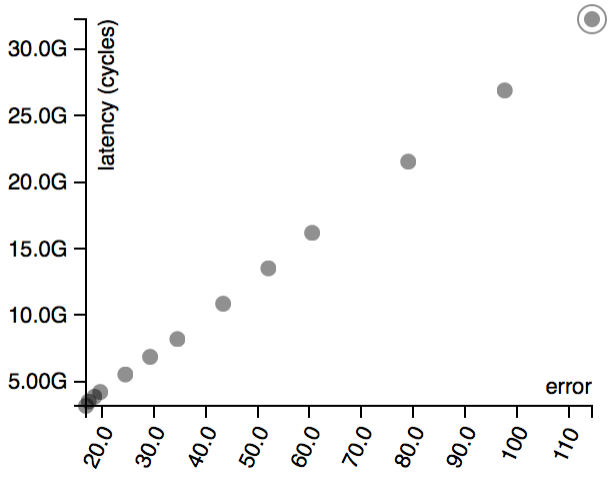
PolyBench and **Livermore loops**, prioritize latency:

Latency
- up to 13x
- average 7x

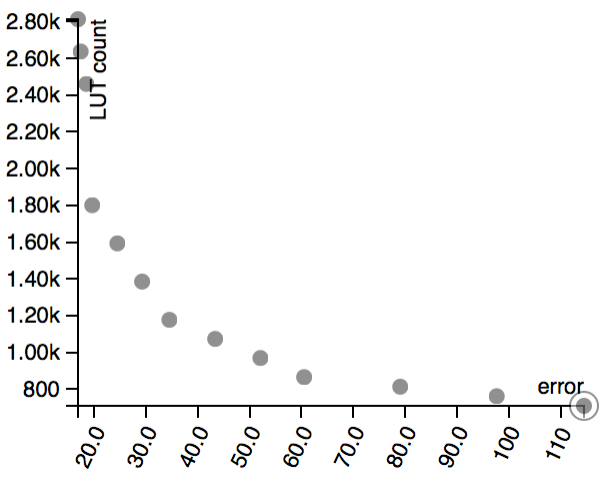
Accuracy
- up to 8x
- average 4x

Resources costs
- up to 4x
- average 3x

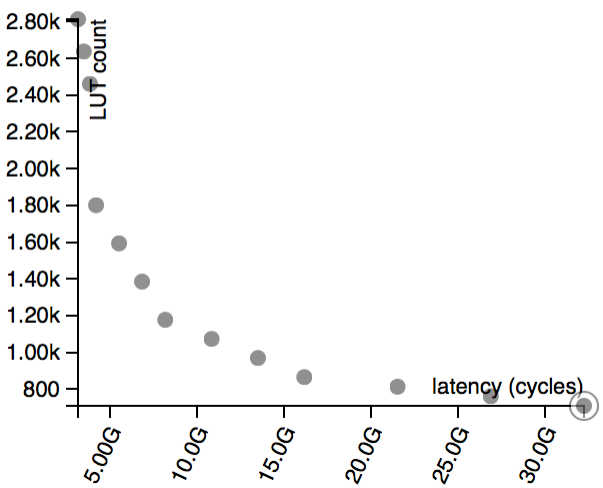
Latency vs. error



LUT count vs. error



LUT count vs. latency



Conclusion

- SOAP3
  - Arithmetic rules
  - Memory access rules
  - Standard program equivalences
  - Optimize numerical C programs for accuracy, resources and latency
- Future work
  - Fixed-point with Multiple precisions
  - Relational Abstract Domains

Tool & Results

https://admk.github.io/soap/