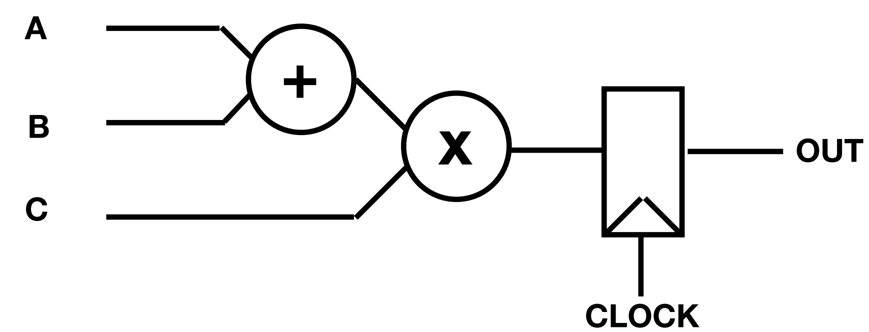
Synthesizable Higher-Order Functions for C++

Dustin Richmond, Alric Althoff, Ryan Kastner

UC San Diego

Description vs Synthesis



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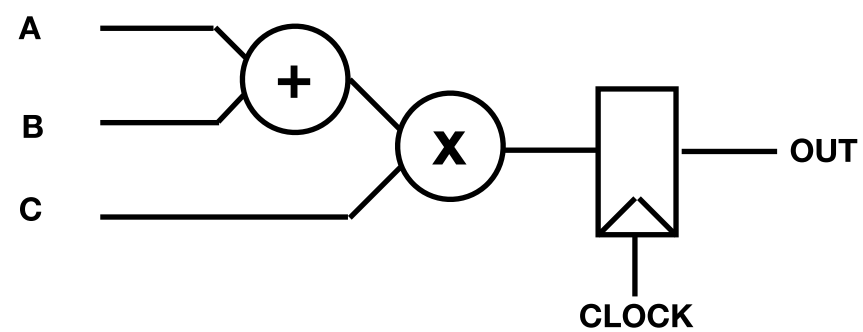


Hardware Description Languages

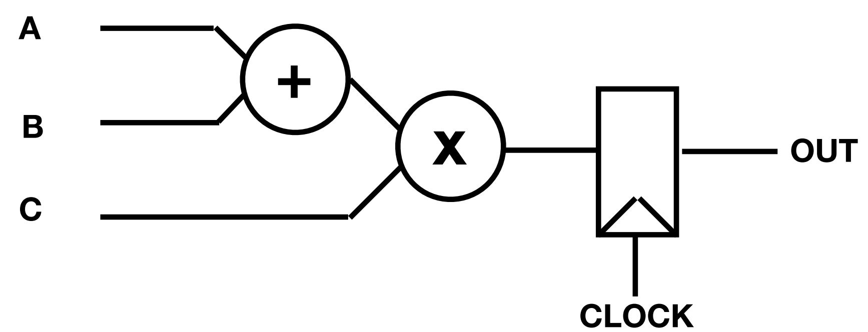
```
module demo
  (input           CLOCK,
   input [31:0]  A,
   input [31:0]  B,
   input [31:0]  C,
   output reg [31:0]  OUT);

   logic [31:0]          wResult;

   assign wResult = (A + B)*C;

   always @(posedge CLOCK) begin
      OUT <= wResult;
   end
endmodule
```

Description vs Synthesis



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   logic [31:0]          wResult;

   assign wResult = (A + B)*C;

   always @(posedge CLOCK) begin
      OUT <= wResult;
   end
endmodule
```

C++ Synthesis Languages

```
unsigned int demo(unsigned int A,
                  unsigned int B,
                  unsigned char C){

  return (A + B)  * C
}
```

Parallel Patterns in Hardware

Genomics Databases Computer Vision Signals Sorting

[1] J. Matai, **D. Richmond,** et al. "Resolve: Generation of high-performance sorting architectures from high-level synthesis," *ISFPGA, 2016*.
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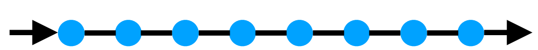
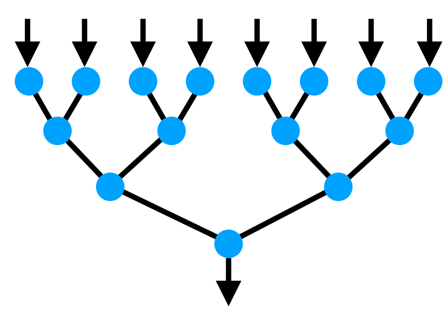
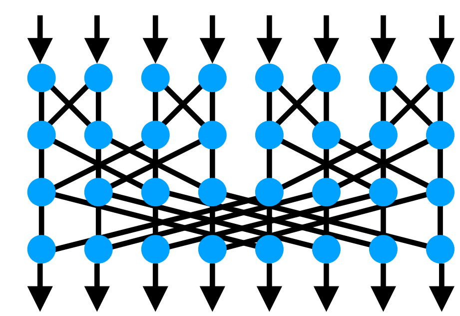


Systolic Array



Reduction Tree



Butterfly Network

[1] J. Matai, **D. Richmond,** et al. "Resolve: Generation of high-performance sorting architectures from high-level synthesis," *ISFPGA, 2016*.
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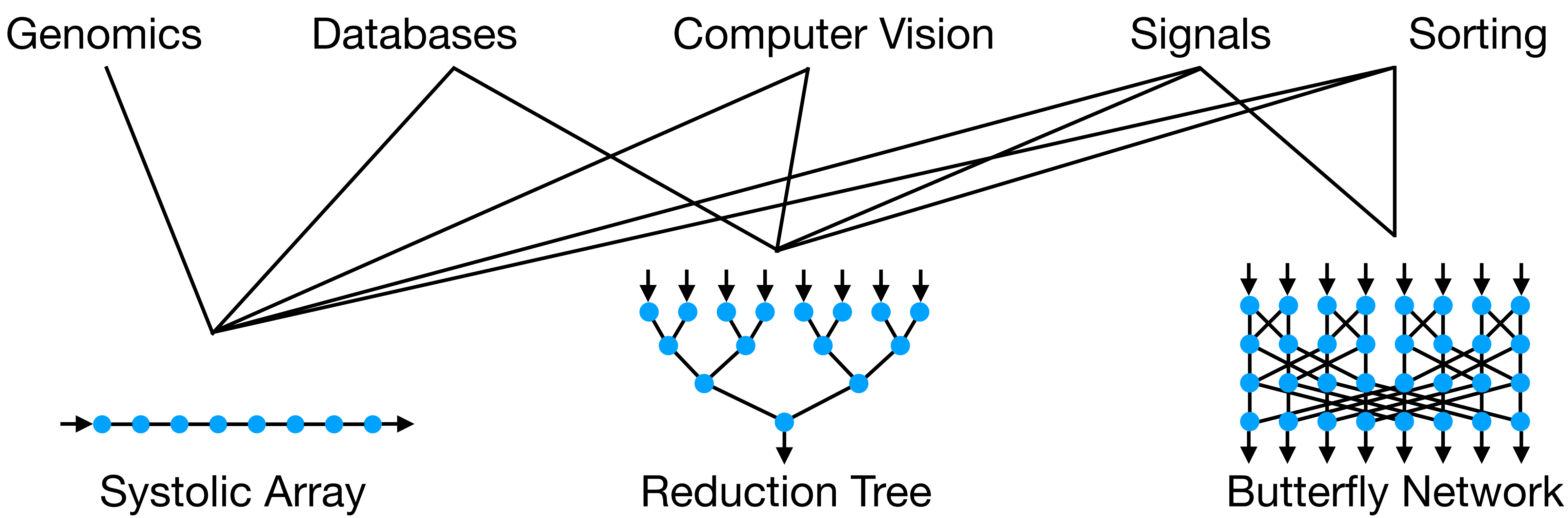
Parallel Patterns in Hardware



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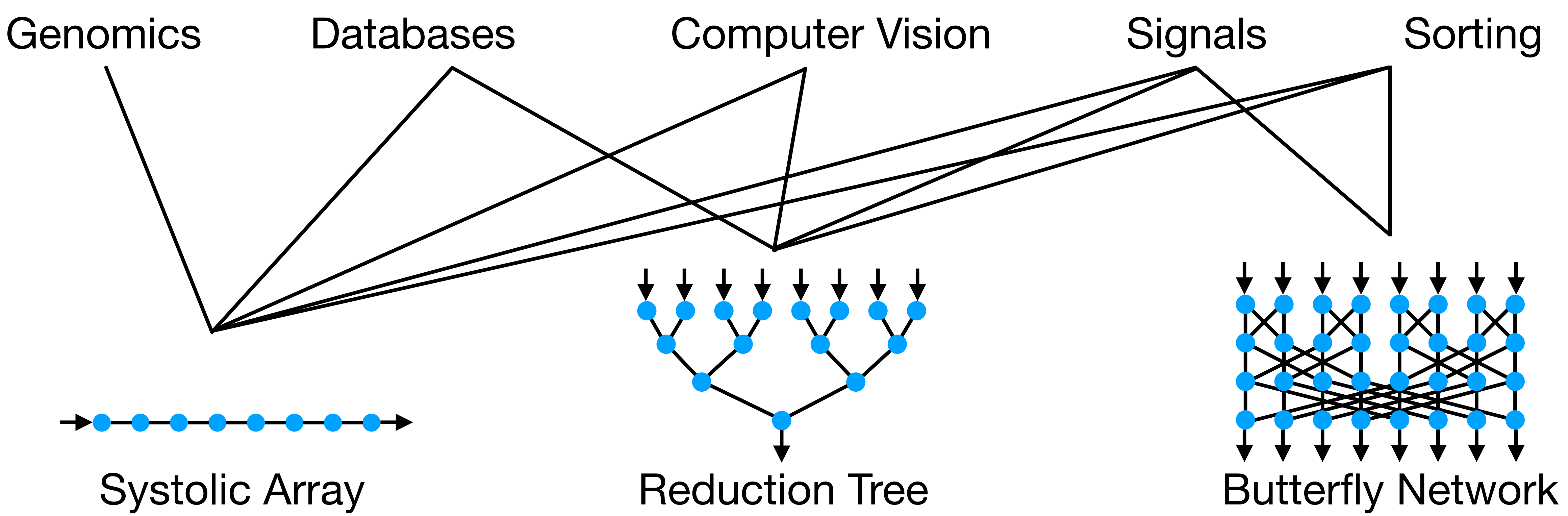
Parallel Patterns in Hardware



Many Applications -> Small Number of Patterns

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Higher-Order Functions as Patterns

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i = 10.0
r = apply(square, i)
# r = 100.0
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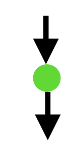
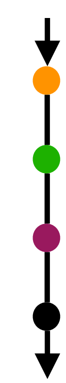


```
a = 1
st1 = compose(square, add1)
st2 = compose(mulby2, st1)
st3 = compose(divby4, st3)
b = st2(a)
# b = 2 ((((a + 1) ^ 2) * 2) / 4)
```



Higher-Order Functions as Patterns

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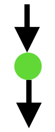

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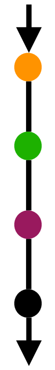
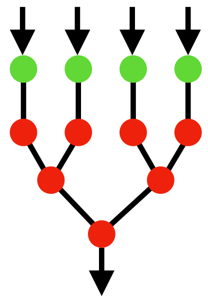


```
l = [1, 2, 3, 4]
m = map(square, l)
r = reduce(sum, m)
# r = 30
```



Pointers and Polymorphism

- Lists
- Recursion (Loops)
- Function-Passsing (First Class Functions)

Research Questions

- Can we create synthesizable Higher-Order Functions?[6, 7]
- How does the syntax compare to Python?
- Is there a performance, area, or frequency cost?

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Function Passing

```
int square(int &input){
  return input*input;
}

int apply(int (*f)(int&), int &input){
  return f(input);
}

int main(){
  int res;
  res = apply(square, 10);
  // res = 100
  return 0;
}
```

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int main(){
  int res;
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  // res = 100
  return 0;
}
```

Pointer! (Not *Synthesizable*)

Function Passing

```
struct Square{
  int operator()(int &input){
    return input*input;
  }
};

int apply(Square &f, int &input){
  return f(input);
}

int main(){
  int res = apply(Square(), 10);
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Function Passing

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int main(){
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  // res = 100
  return 0;
}
```

Object Reference (Synthesizable)

Polymorphism

```
struct Square{
  template <typename TI>
  TI operator()(TI &input){
    return input*input;
  }
};

template <typename FN, typename TI>
auto apply(FN &f, TI &input){
  return f(input);
}

int main(){
  int res = apply(Square(), 10);
  // res = 100
  return 0;
}
```

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struct Square{
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Type Templates

Polymorphism

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Return-Type Inference

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Type Templates

Return-Type Inference

Template Inference

Interested?

Come visit my poster!

Implementation: `reduce`

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```
template <size_t LEN>
struct ReduceHelper{
    template<typename FN, typename TI, typename TA>
    auto operator()(FN &F, TI INIT, array<TA, LEN> IN){
        return ReduceHelper<FN, LEN-1>()(
            F(INIT, head(IN)), tail(IN));
    }
};

template <>
struct ReduceHelper<0>{
    template<typename FN, typename TI, typename TA>
    TI operator()(FN &F, TI INIT, array<TA, 0> IN){
        return INIT;
    }
};

template <typename FN, typename TI, typename TA, size_t LEN>
auto reduce(FN &F, TI INIT, array<TA, LEN> IN){
    return ReduceHelper<LEN>()(F, INIT, IN);
}
```

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Return-Type Inference

Type Templates

Object Reference

Implementation: `reduce`

Static Recursion

Return-Type Inference

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```

Arrays/Lists

Object Reference

Complexity Begets Simplicity

```
array<int, 4> l = {1, 2, 3, 4};
r = reduce(add, l, 0);
// r = 10
```

Complexity Begets Simplicity

```
array<int, 4> l = {1, 2, 3, 4};
r = reduce(std::plus<int>(), l, 0);
// r = 10
```

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Syntax Comparison

Python	**C++**

Syntax Comparison

	Python	C++

Functions	`def add(l, r):`
	`    return (l + r)`
		`struct Add{`
		`  int operator()(int l, int r){`
		`    return (l + r);`
		`  }`
		`} add;`

Syntax Comparison

	Python	C++

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		`struct Add{`
		`  int operator()(int l, int r){`
		`    return (l + r);`
		`  }`
		`} add;`

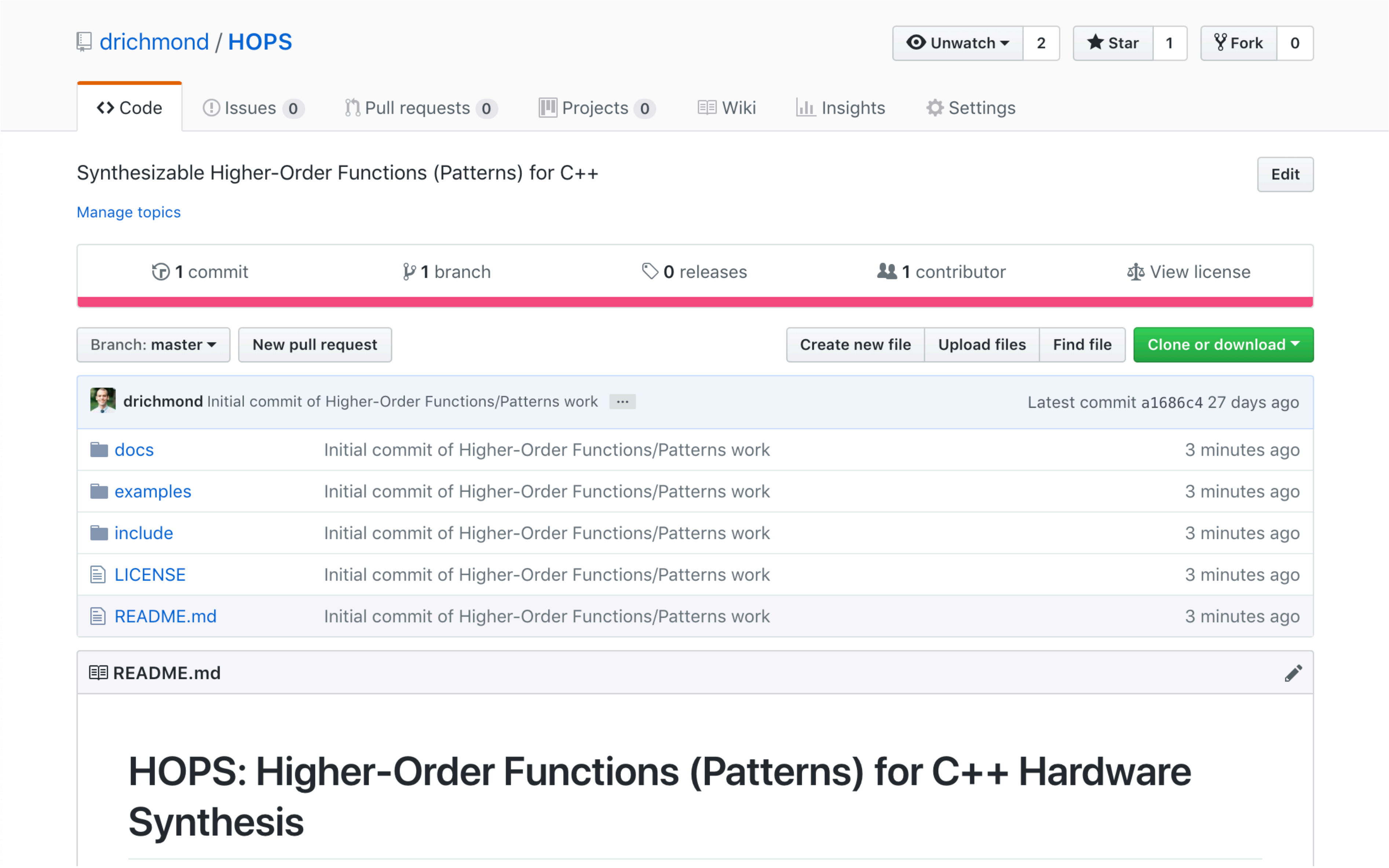
Map-Reduce	`l = [1, 2, 3, 4]`
	`m = map(square, l)`
	`r = reduce(add, m)`
		`array<int, 4> l = {1, 2, 3, 4};`
		`array<int, 4> m, r;`
		`m = map(square, l);`
		`r = reduce(add, m);`

Syntax Differences

- Wrapped Functions (a.k.a “Functors”)
- Explicit Typing
- No Tuples*

Clone our work!

github.com/drichmond/hops



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Cost Analysis

- 6 Application Functions
- 13 Maximum Frequency Datapoints
- Null Hypothesis: Mean max frequencies are not equal

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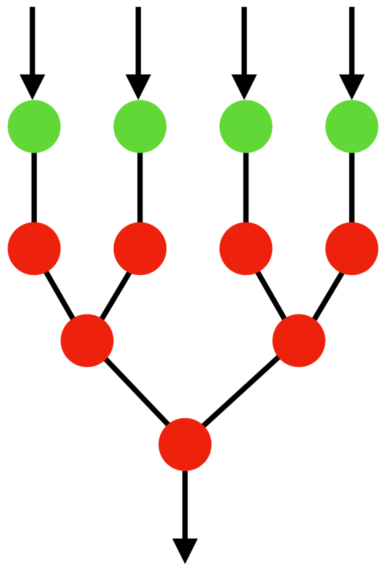
Experimental Setup

“Traditional”
(Trad.)

```
for(/*...*/){
  // Map Implementation
}

for(/*...*/){
  // Reduce Implementation
}
```



Higher-Order Functions
(H.O.F.)

```
m = map(/*Map Fn*/, l);
r = reduce(/*Reduce Fn*/, m);
```

Performance: Throughput & Latency

	Throughput (Results/Cycle)		Latency (Cycles)	
	H.O.F	Traditional	H.O.F.	Traditional
Finite Impulse Response Filter	1	1	65	65
Insertion Sort	1	1	31	31
Smith Waterman	1	1	16	16
ArgMin	1	1	7	7
Fast Fourier Transform	1	1	59	59
Bitonic Sort	1	1	21	21

Area: Resources Consumed

	Flip-Flops		SRL		LUT		DSPs	
	H.O.F.	Trad.	H.O.F.	Trad.	H.O.F.	Trad.	H.O.F.	Trad.
Finite Impulse Response Filter	14388	14388	**227**	**272**	**7306**	**7305**	48	48
Insertion Sort	2300	2300	0	0	935	935	0	0
Smith Waterman	895	895	11	11	**1187**	**1186**	0	0
ArgMin	**2670**	**2666**	**8**	**10**	**1575**	**1573**	0	0
Fast Fourier Transform	**21263**	**21240**	**2487**	**2494**	8096	8096	77	77
Bitonic Sort	11929	11929	1	1	4869	4869	0	0

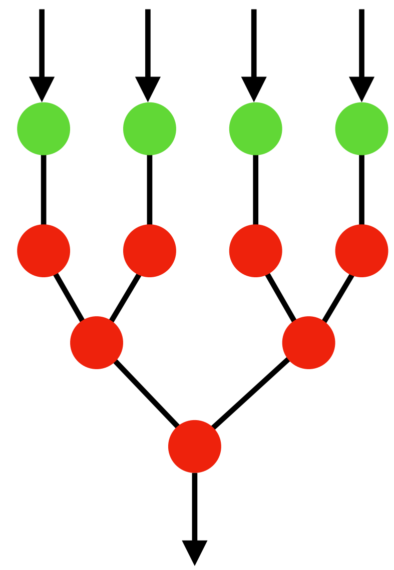
Maximum Frequency

	Higher-Order Function		Traditional		$\alpha < .05$
	Mean (μ, MHz)	Std Dev (MHz)	Mean (μ, MHz)	Std. Dev (MHz)	$\mu_{Loop} \neq \mu_{H.O.F.}$
Finite Impulse Response Filter	166.80	3.12	165.56	3.57	0.01
Insertion Sort	162.83	3.22	166.47	5.02	0.008
Smith Waterman	103.73	4.19	103.58	5.34	0.025
ArgMin	110.64	2.51	110.91	2.89	0.02
Fast Fourier Transform	123.56	3.35	123.56	3.18	**0.05**
Bitonic Sort	112.77	3.50	113.85	2.76	0.01

Conclusion:

No performance, area, or frequency cost

Synthesizable Higher-Order Functions for C++



- C++ Higher-Order Functions use Meta-Programming
- Provide a Python-like syntax
- No performance, area, or frequency cost

github.com/drichmond/hops