Towards Implicit Parallel Programming for Systems

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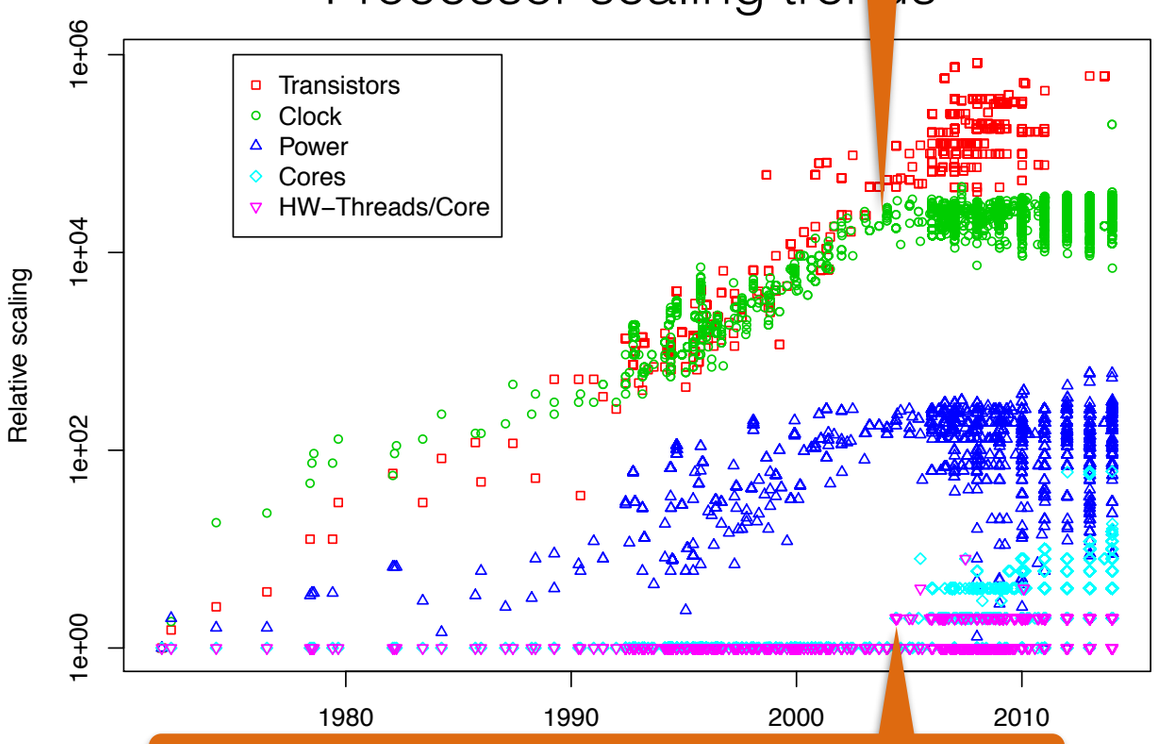
Fachreferent : Prof. Dr.-Ing. Hermann Härtig

4.9.2019

The Shape Of Things To Run

The end of the single-core era



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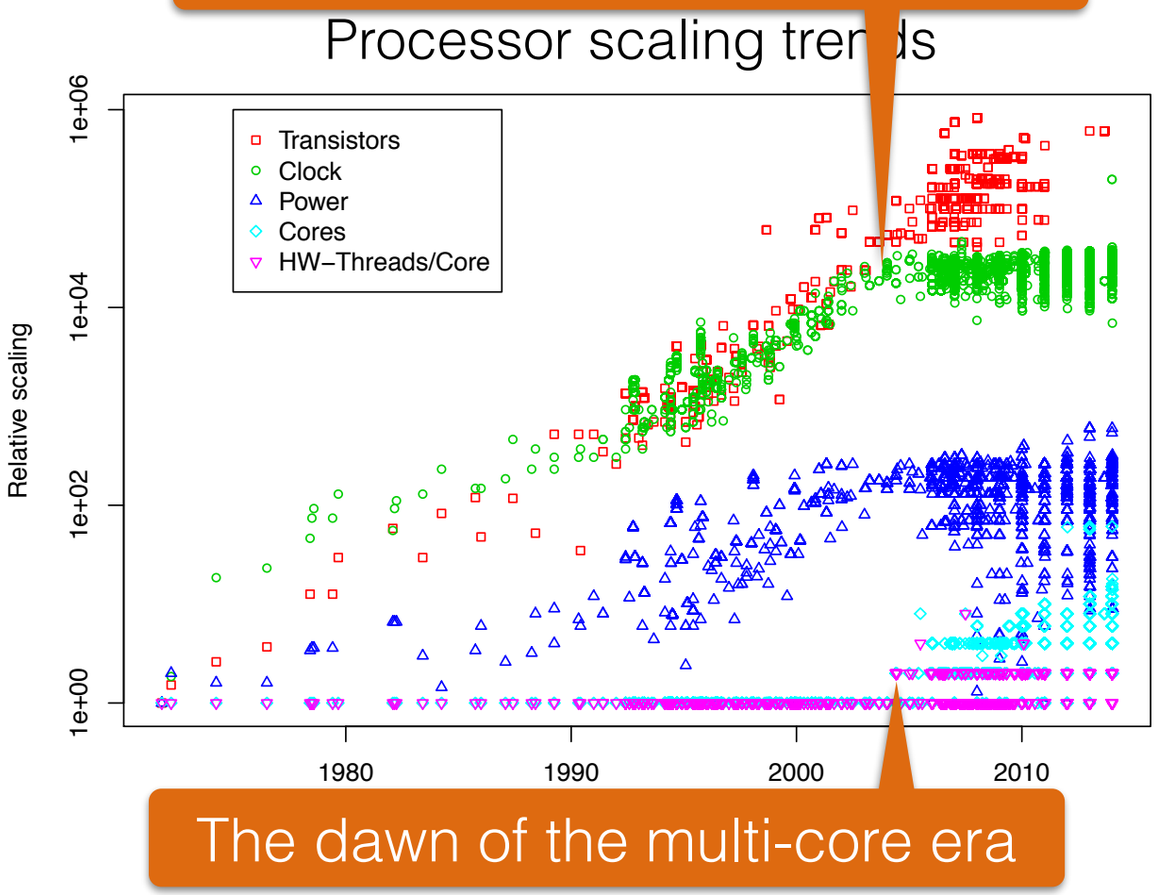

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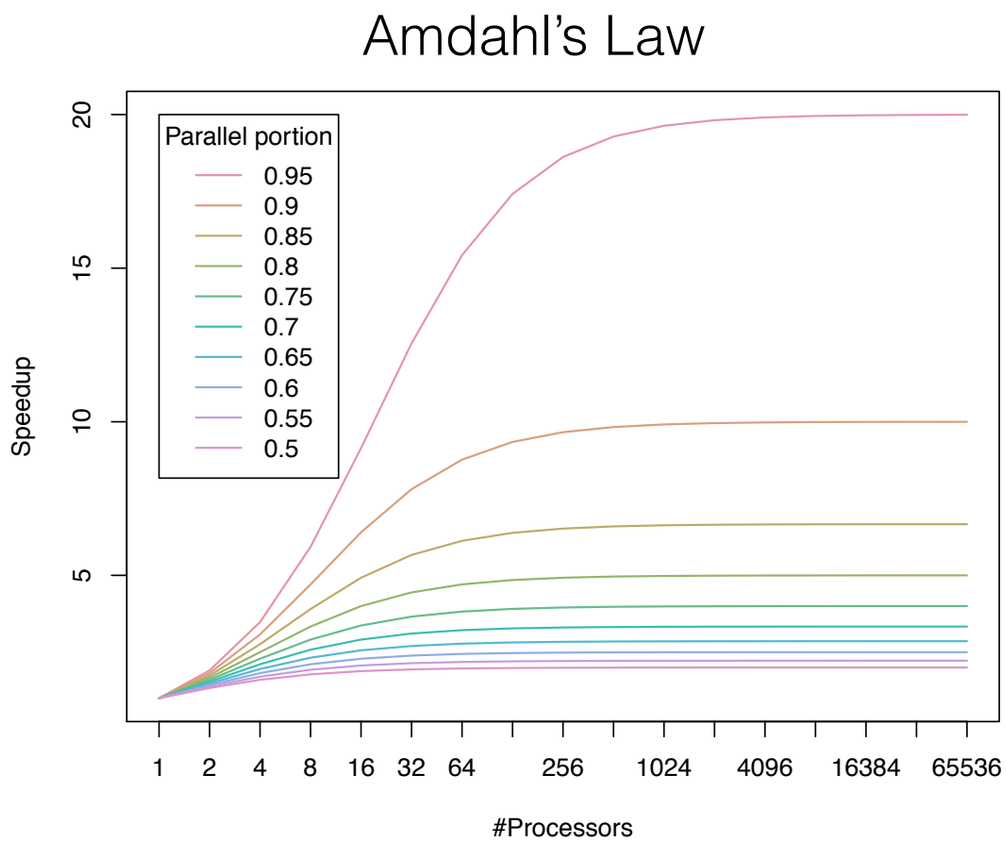

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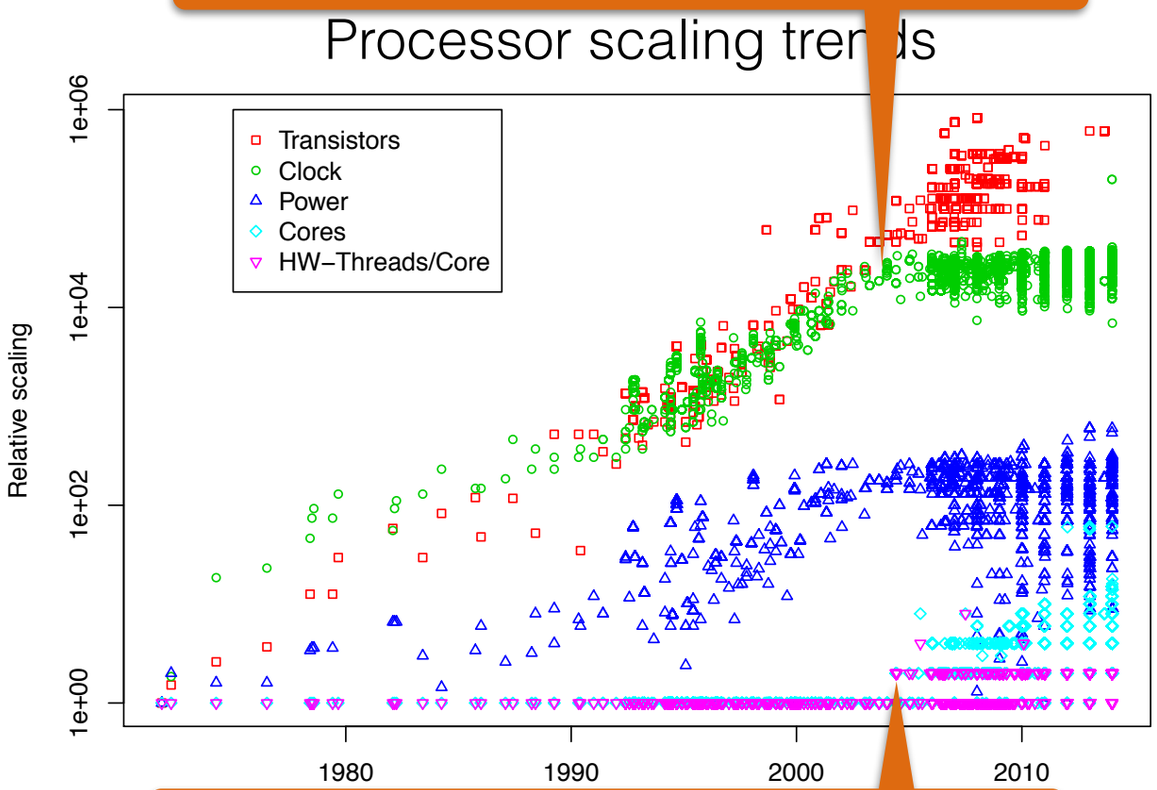

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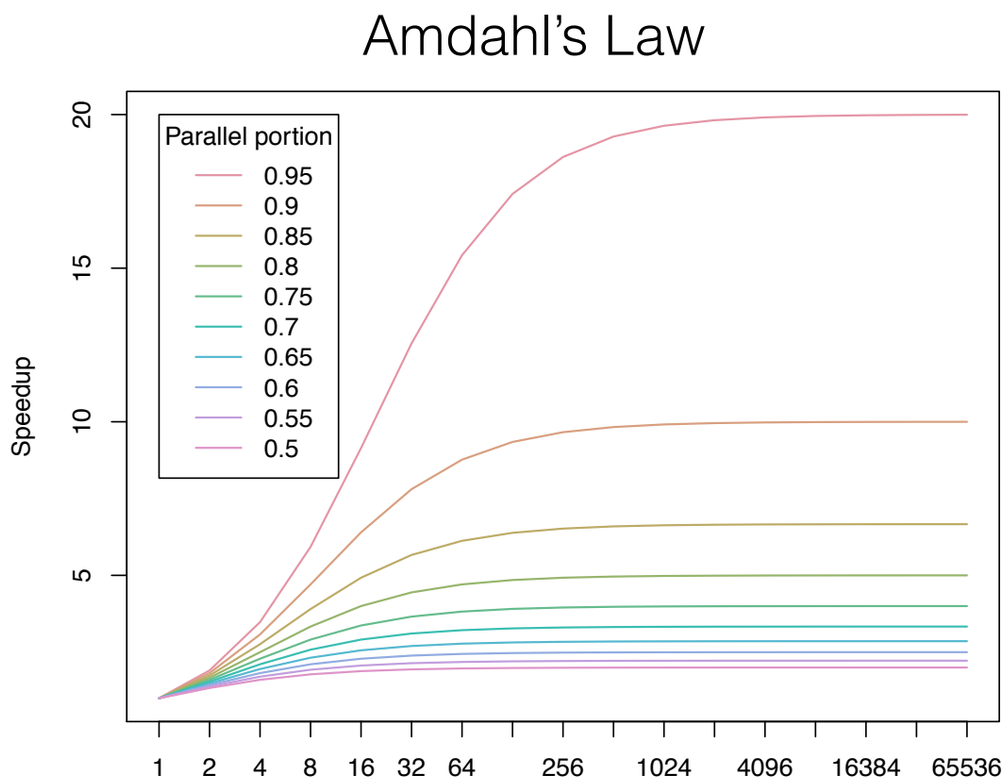

Challenge	Near-Term	Long-Term
1,000-fold software parallelism	Data parallel languages and "mapping" of operators, library and tool-based approaches	New high-level languages, compositional and deterministic frameworks

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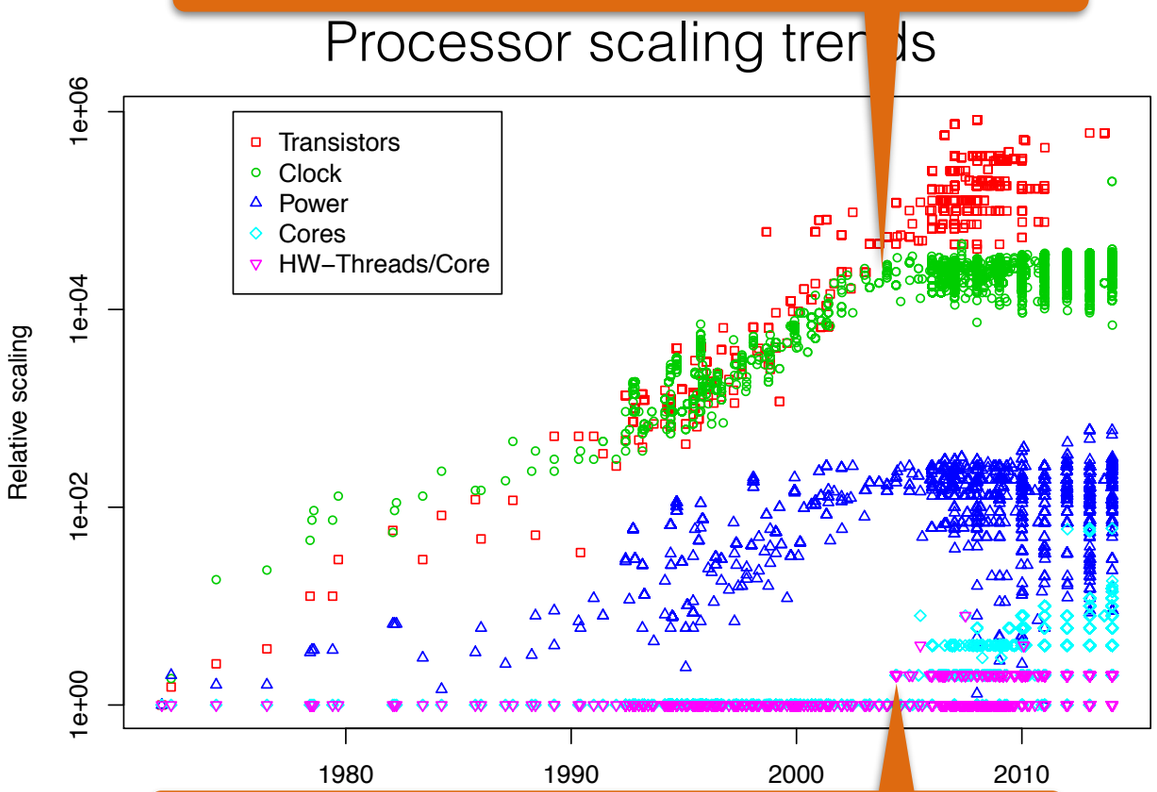

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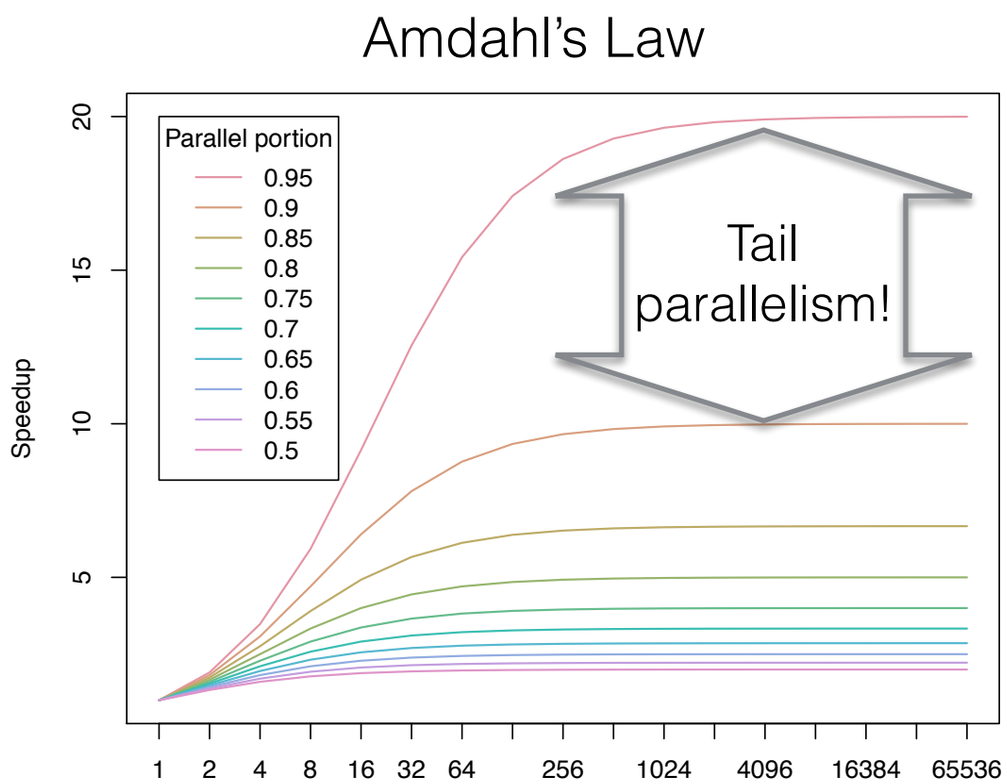

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Programming Is Simple!

Programming

Variables
Functions
Function Calls

Conditionals
Loops

Classes
Objects
Methods

Parallel Programming Is Hard!

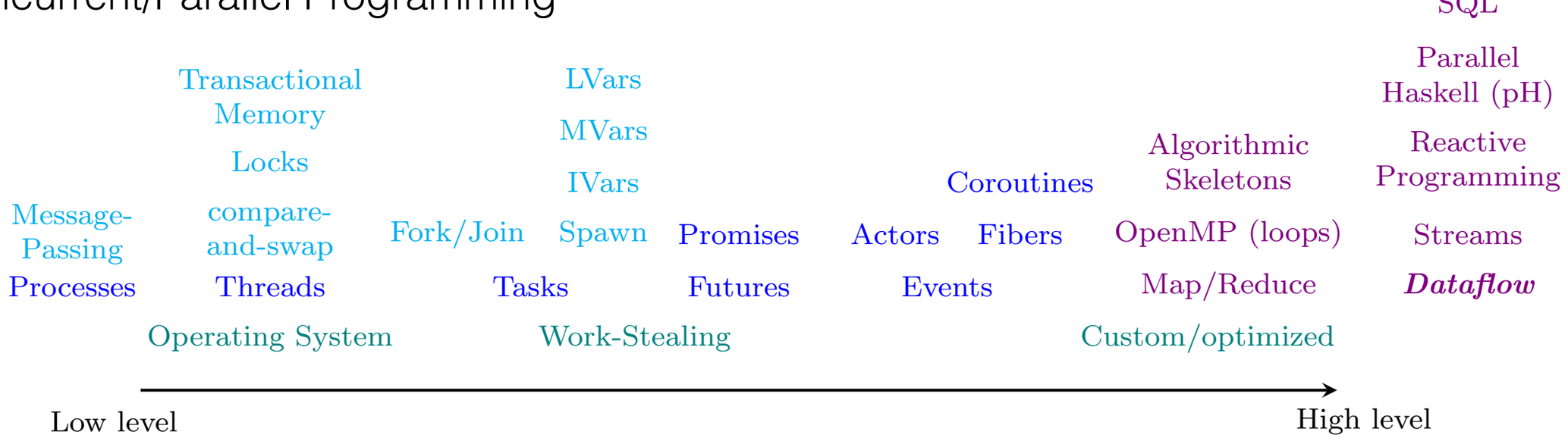
Programming

Variables
Functions
Function Calls

Conditionals
Loops

Classes
Objects
Methods

Concurrent/Parallel Programming



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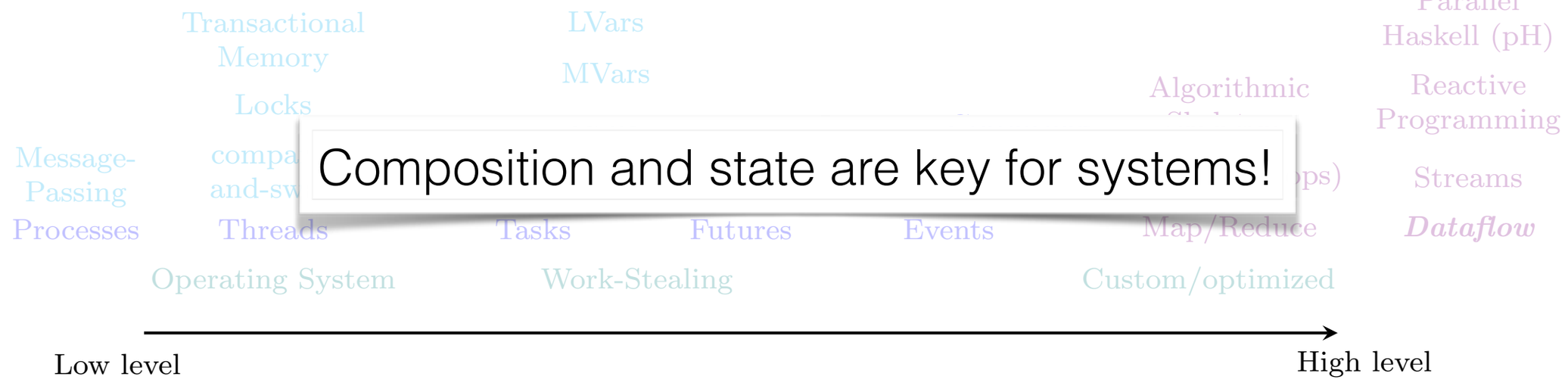

Composition and state are key for systems!

Parallel Programming Is Hard!

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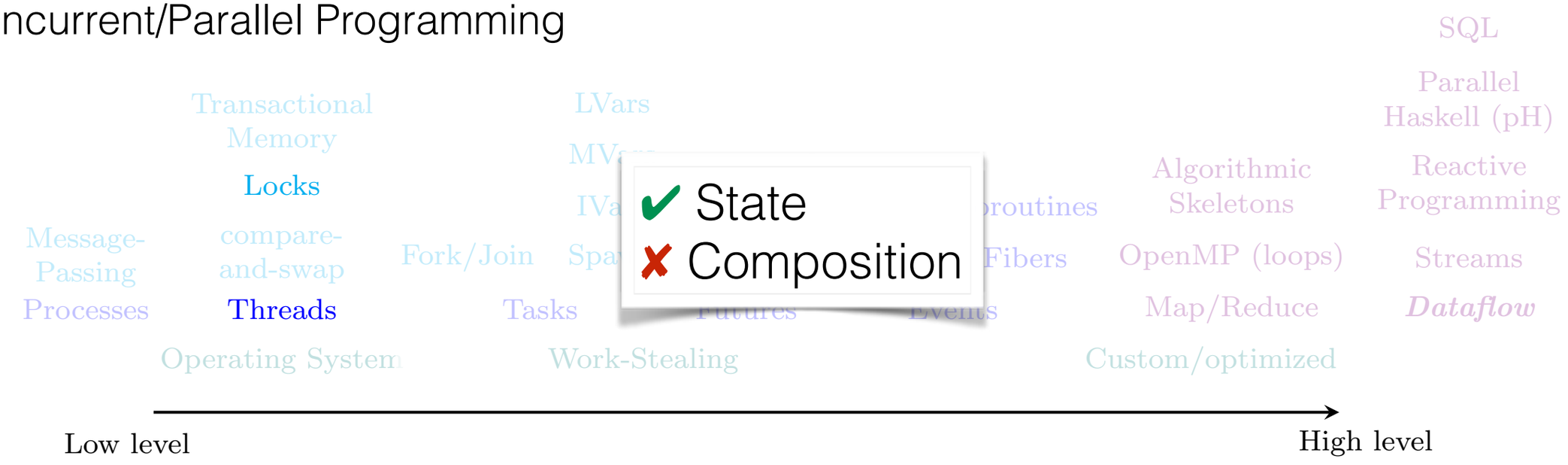
⇩

Concurrent/Parallel Programming



Lee EA. The problem with threads. Computer. 2006.

Van Renesse R. Goal-oriented programming, or composition using events, or threads considered harmful. In ACM SIGOPS European Workshop 1998.

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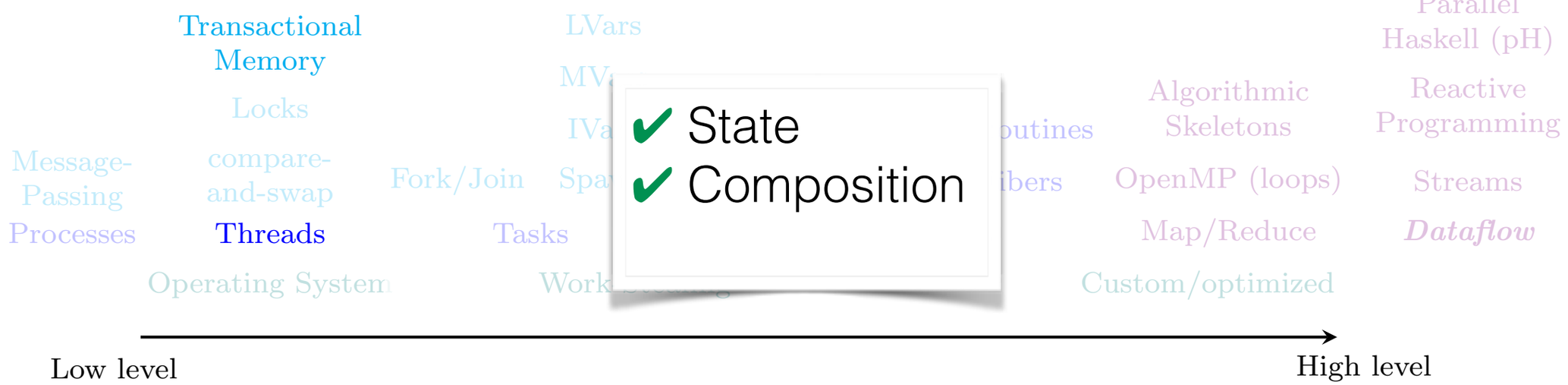

Herlihy M, Moss JE. Transactional memory: Architectural support for lock-free data structures. ACM; 1993 Jun 1.

Shavit N, Touitou D. Software transactional memory. Distributed Computing. 1997 Feb 1;10(2):99-116.

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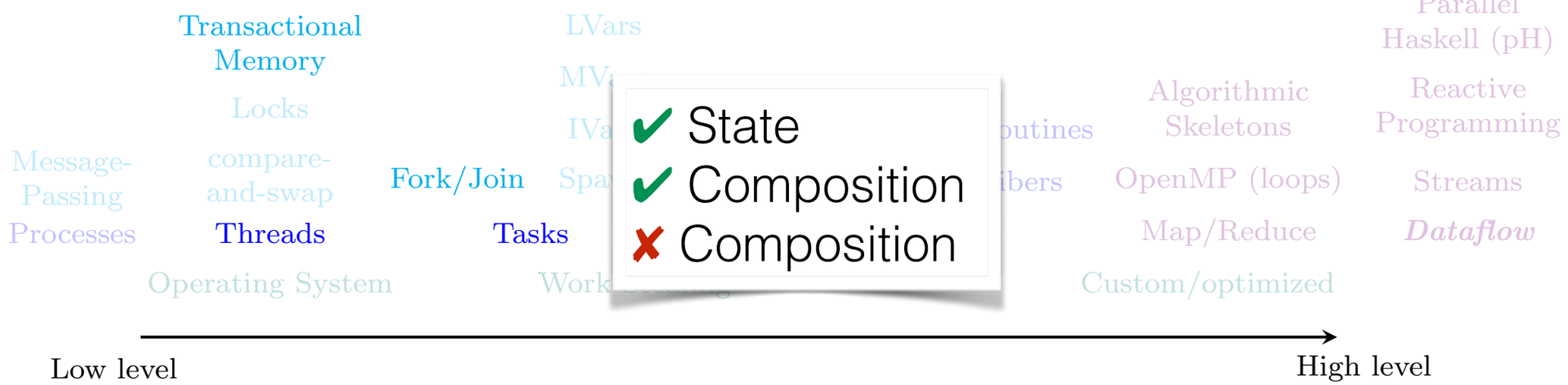

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J. Swalens, J. De Koster, and W. De Meuter. 2016. Transactional Tasks: Parallelism in Software Transactions. In Proceedings of ECOOP'16.

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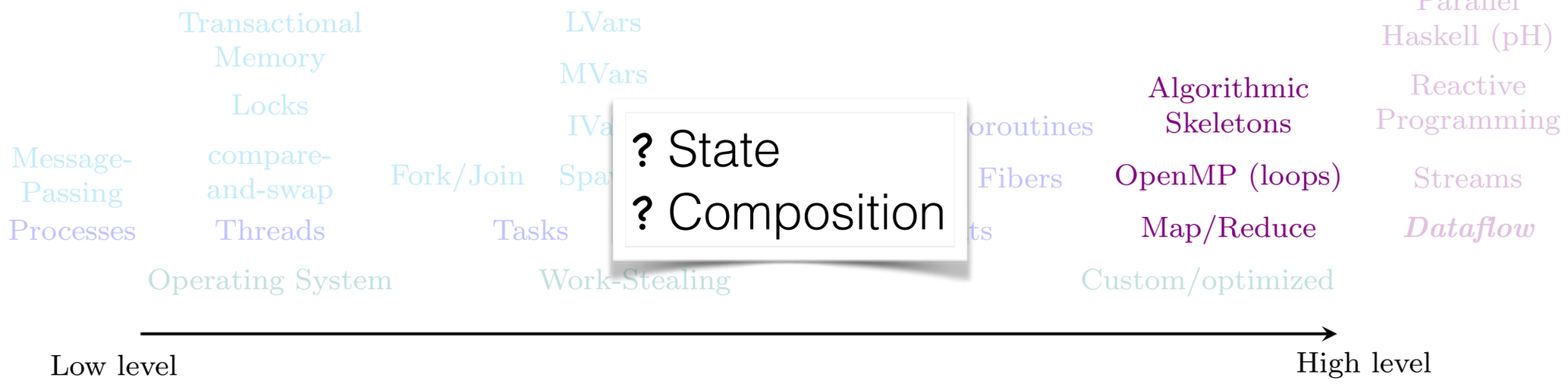

Mou ZG, Hudak P. An algebraic model for divide-and-conquer and its parallelism. The Journal of Supercomputing. 1988.

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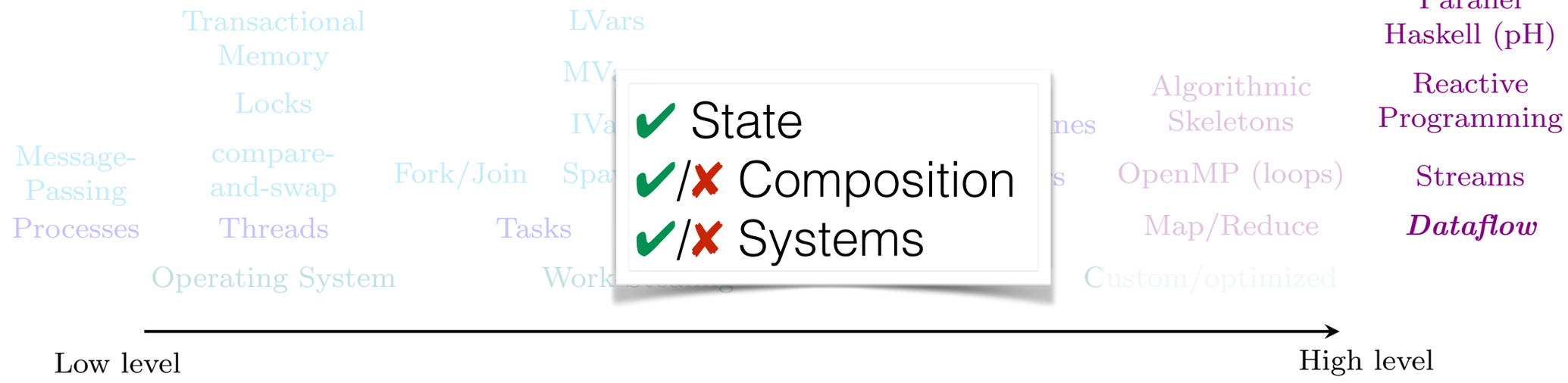

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Chambers C, Raniwala A, Perry F, Adams S, Henry RR, Bradshaw R, Weizenbaum N. FlumeJava: easy, efficient data-parallel pipelines. In ACM Sigplan Notices 2010. ACM.

Coutts D, Leshchinskiy R, Stewart D. Stream fusion: From lists to streams to nothing at all. In ACM SIGPLAN Notices 2007. ACM.

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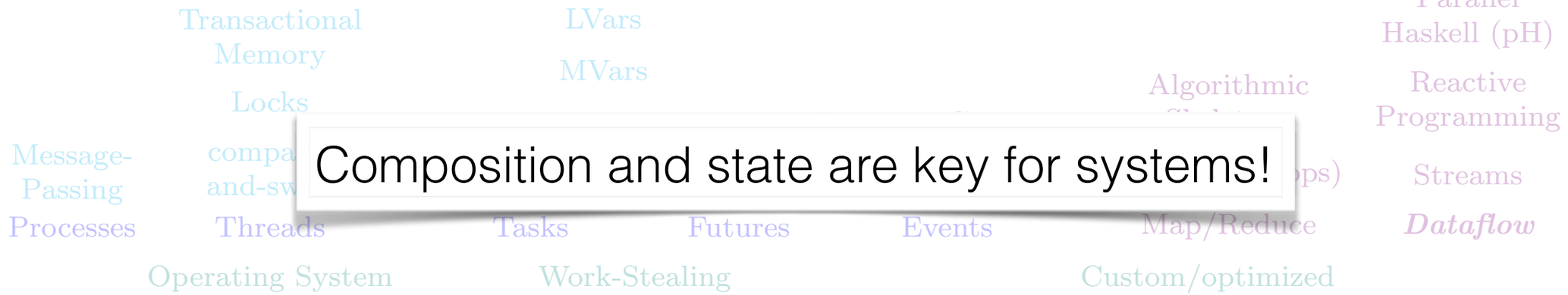

Explicit

Concurrency Bugs

Implicit

Optimizations
(Sequential ➪ Parallel)

Michel Steuwer, Toomas Remmelg, and Christophe Dubach. 2017. Lift: a functional data-parallel IR for high-performance GPU code generation. CGO '17.

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Concurrent/Parallel Programming

Transactional Memory
Locks
Message-Passing
Processes
Threads
Operating System
MVars
Tasks
Futures
Work-Stealing
Events
Algorithmic
Map/Reduce
Custom/optimized
SQL
Parallel
Haskell (pH)
Reactive Programming
Streams
Dataflow

Composition and state are key for systems!

Low level → High level

Explicit

Concurrency Bugs

PL/compiler co-design!

Implicit

Optimizations
(Sequential ➪ Parallel)

Mary Hall, David Padua, and Keshav Pingali. 2009. Compiler research: the next 50 years. Commun. ACM.

Ingredients for Implicit Parallel Programming

Programming Model/ Language

- No concurrency abstractions.
- Practicality:
  - Integration into existing programming models (e.g., OOP)/ languages.
  - Gradual switch/ reuse of existing code base.

Ingredients for Implicit Parallel Programming

Programming Model/ Language → Compiler

- No concurrency abstractions.
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  - Integration into existing programming models (e.g., OOP)/ languages.
  - Gradual switch/ reuse of existing code base.

- Intermediate Representation (IR) needs a solid well-studied theoretical foundation for
- provable semantic-preserving transformations
- even for programs with side-effects.

Ingredients for Implicit Parallel Programming

Programming Model/ Language → Compiler → Runtime System

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- Intermediate Representation (IR) needs a solid well-studied theoretical foundation for
- provable semantic-preserving transformations
- even for programs with side-effects.

- Flexible/dynamic runtime representation.
- Efficient parallel execution of independent computations.
- Deterministic execution.
- Concurrent I/O.


Programming Model/
Language
Compiler
Runtime System

Programming Model/
Language

Compiler

Runtime System

Programming Model/
Language

Compiler

Runtime System

- Parallelism
- Mapping/Scheduling
-

Database Systems

Data Management Systems

Data Streaming Systems

Server Systems

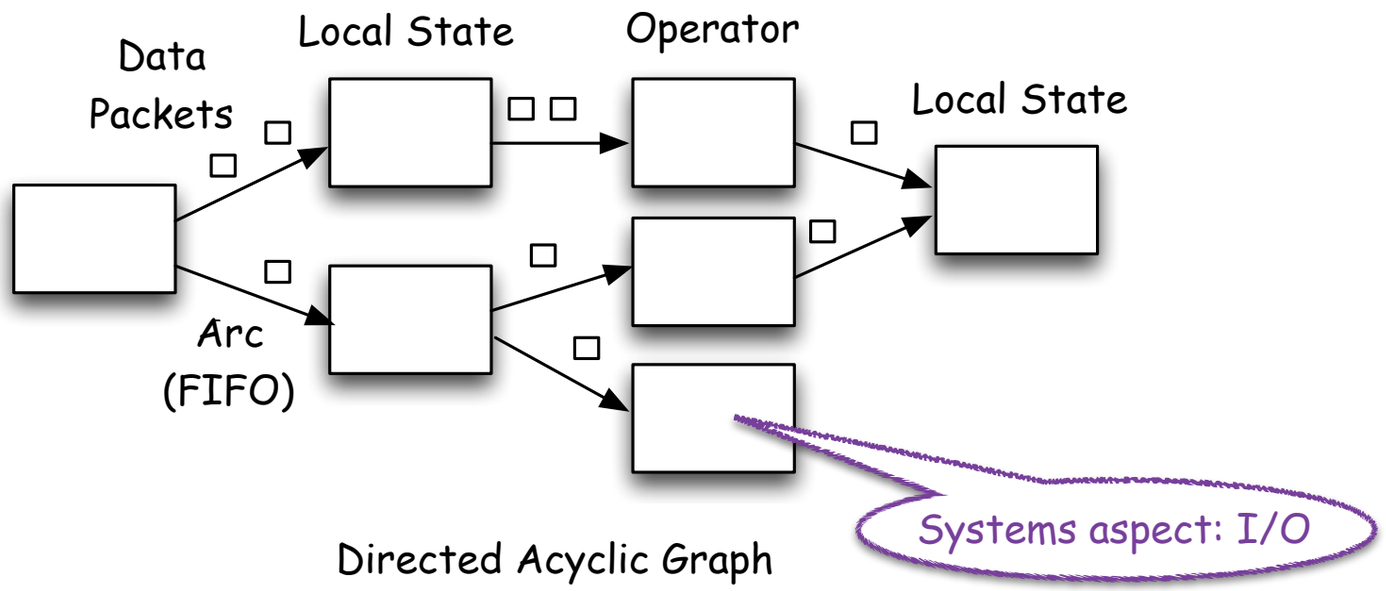
Parallelism

Embedded Systems

Signal Processing Systems

Heterogeneous Architectures

Dataflow



Database Systems | Data Management Systems | Data Streaming Systems | Server Systems

Embedded Systems | Signal Processing Systems

Parallelism

Heterogeneous Architectures

J. B. Dennis. Data flow supercomputers. Computer, 13(11):48–56, Nov. 1980.

J. P. Morrison. Flow-Based Programming. Nostrand Reinhold, 1994

Arvind and D. E. Culler. Annual review of computer science vol. 1, 1986. chapter Dataflow architectures. Annual Reviews Inc.

Programming Model/
Language

Compiler

Runtime System

- Parallelism
- Mapping/Scheduling
-

Programming Model/ Language → Compiler → Runtime System

Dataflow
- Parallelism
- Mapping/Scheduling
- Dynamic Software Evolution

Sebastian Ertel and Pascal Felber. 2014. A framework for the dynamic evolution of highly-available dataflow programs. In Proceedings of the 15th International Middleware Conference (Middleware '14). ACM.

Sebastian Ertel, Christof Fetzer, and Pascal Felber. 2015. Ohua: Implicit Dataflow Programming for Concurrent Systems. In Proceedings of the Principles and Practices of Programming on The Java Platform (PPPJ '15). ACM.

Programming Model/
Language

Compiler

Runtime System

Dataflow

- Parallelism
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- Dynamic Software Evolution

Programming Model/
Language

Compiler

Runtime System

Dataflow

- Flexible/dynamic runtime representation.
- Efficient parallel execution of independent computations.
- Deterministic execution.
- Concurrent I/O.

Programming Model/
Language

Compiler

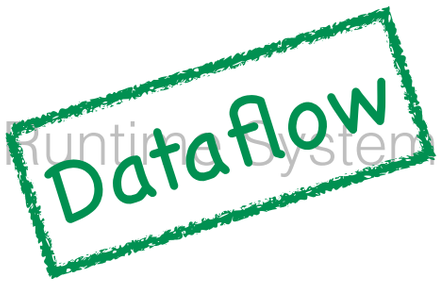
Runtime System

Dataflow

Dataflow:
- Not concise
- Limited scalability
- Concurrency abstraction

Programming Model/
Language

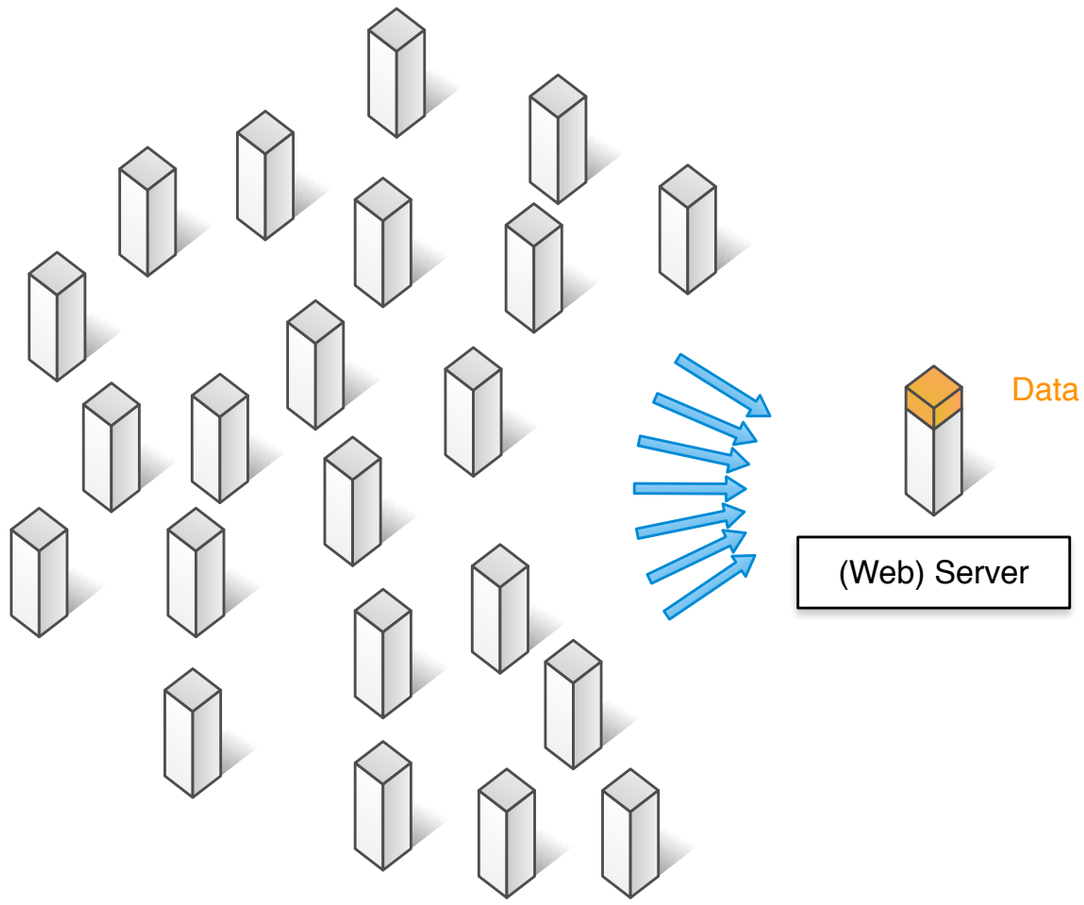
Compiler



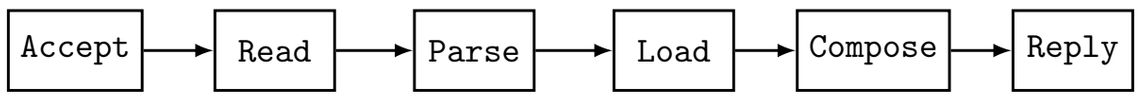
SFP:

- Variables
- Functions
- State

Server Architecture



Explicit Dataflow Construction



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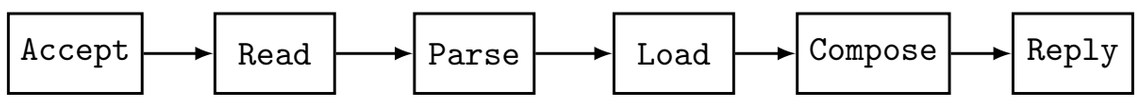


```
public class WebServer extends StreamFlexGraph {
  private Filter a, r, p, l, c, rep;

  public WebServer() {
    a   = makeFilter(Accept.class);
    r   = makeFilter(Read.class);
    p   = makeFilter(Parse.class);
    l   = makeFilter(Compose.class);
    rep = makeFilter(Reply.class);
    connect(a, r);
    connect(r, p);
    connect(p, l);
    connect(l, c);
    connect(c, rep);
    validate();
  }

  public void start() {
    new Synthesizer(a).start();
    super.start();
  }
}
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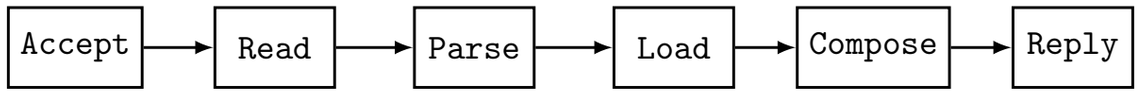
Implicit Dataflow Construction

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}
```
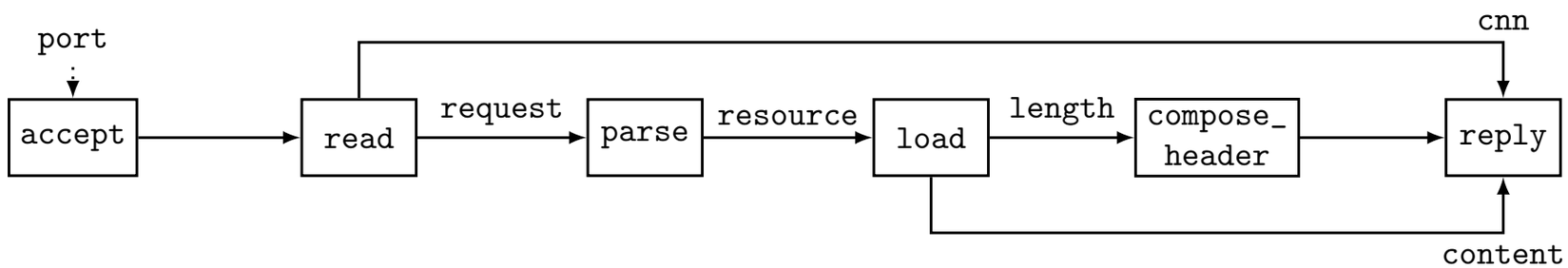

```
fn server(port) {
  let (cnn, request)    = read(accept(port));
  let resource          = parse(request);
  let (content, length) = load(resource);
  reply(cnn, compose_header(length), content)
}
```



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Classic Operators

```
class FileLoad extends Filter {

  private Channel<String> in, out;

  public void work() {
    // explicit channel control
    String resource = in.take();
    String contents = load(resource);
    out.put(contents);
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Explicit dataflow

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  private Map<String, String> cache = new HashMap<>();

  private String load(String resource){
    String content = null;
    if(!cache.containsKey(resource)){
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          Files.readAllBytes(Paths.get(resource))
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      cache.put(resource,content);
      // cache eviction emitted for brevity
    } else {
      content = cache.get(resource);
    }
    return content;
  }

}
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➪ Explicit dataflow

➪ Computation

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Stateful Functions

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class FileLoad {
  Map<String, String> cache = new HashMap<>();

  String load(String resource) {
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Computation

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Computation

Computation is (almost) a function:

- ✘ Some loss of dataflow expressiveness.
- ✔ Solid theoretical foundation.
- ✔ Deterministic.

Stateful Functions

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    return content;
  }

}
```

```
class FileLoad {
  Map<String, String> cache = new HashMap<>();

  String load(String resource) {
    String contents = null;
    // load file data from disk or cache (omitted)
    return contents;
  }
}
```

```
struct FileLoad {
   cache : HashMap,
};

impl FileLoad {
  fn load(&self, resource:String) -> String {
    let contents : String = {
    // load file data from disk or cache (omitted)
    };
    contents
  }
}
```

Stateful Functions

```
class FileLoad extends Filter {

  private Channel<String> in, out;

  public void work() {
    // explicit channel control
    String resource = in.take();
    String contents = load(resource);
    out.put(contents);
  }

  private Map<String, String> cache = new HashMap<>();

  private String load(String resource){
    String content = null;
    if(!cache.containsKey(resource)){
      content = new String(
          Files.readAllBytes(Paths.get(resource))
        );
      cache.put(resource,content);
      // cache eviction emitted for brevity
    } else {
      content = cache.get(resource);
    }
    return content;
  }

}
```

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class FileLoad {
  Map<String, String> cache = new HashMap<>();

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impl FileLoad {
  fn load(&self, resource:String) -> String {
    let contents : String = {
    // load file data from disk or cache (omitted)
    };
    contents
  }
}
```

```
char* load(char* resource) {
  static GHashTable* cache = g_hash_table_new();
  char* contents = NULL;
  // load file data from disk or cache (omitted)
  return contents;
}
```

Stateful Functions

?

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class FileLoad extends Filter {

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      // cache eviction emitted for brevity
    } else {
      content = cache.get(resource);
    }
    return content;
  }

}
```

State encapsulation

```
class FileLoad {
  Map<String, String> cache = new HashMap<>();

  String load(String resource) {
    String contents = null;
    // load file data from disk or cache (omitted)
    return contents;
  }
}
```



```
struct FileLoad {
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impl FileLoad {
  fn load(&self, resource:String) -> String {
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    };
    contents
  }
}
```

```
char* load(char* resource) {
  static GHashTable* cache = g_hash_table_new();
  char* contents = NULL;
  // load file data from disk or cache (omitted)
  return contents;
}
```

Local State

```
fn server(port) {
  let (cnn, req)         = read(accept(port));
  let resource           = parse(req);
  let (content, length) = load(resource);
  reply(cnn, compose(length), content)
}
```

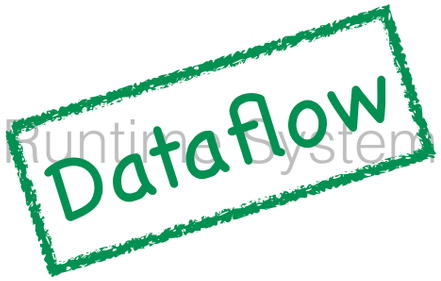
```
struct FileLoad {
   cache : HashMap,
};

impl FileLoad {
  fn load(&self, resource:String) -> String {
    let contents : String = {
    // load file data from disk or cache (omitted)
    };
    contents
  }
}
```

State is local to each call-site!

Programming Model/
Language

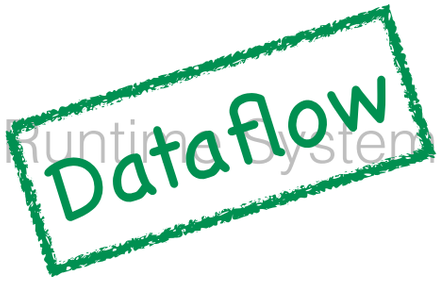
Compiler



SFP:
- Variables
- Stateful Functions
- Composition

Programming Model/
Language

Compiler



SFP:
- Variables
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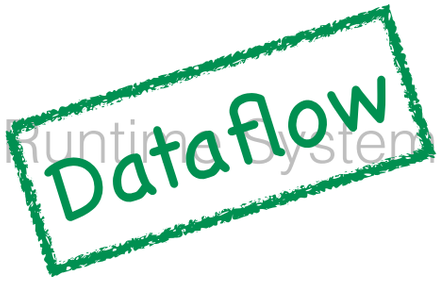
SFP: Stateful Functional Programming

Programming Model/
Language

Compiler



SFP:
- Variables
- Stateful Functions
- Composition
- Code reuse!

SFP: Stateful Functional Programming

Algorithms

```
fn server(port) {
  let (cnn, req)         = read(accept(port));
  let resource           = parse(req);
  let (content, length) = load(resource);
  reply(cnn, compose_header(length), content)
}
```

Top-level Algorithms

```
fn respond(cnn, content, length){
  reply(cnn, compose_header(length), content)
}

fn server(port) {
  let (cnn, req)         = read(accept(port));
  let resource           = parse(req);
  let (content, length) = load(resource);
  respond(cnn, content, length)
}
```

Lambda Algorithms

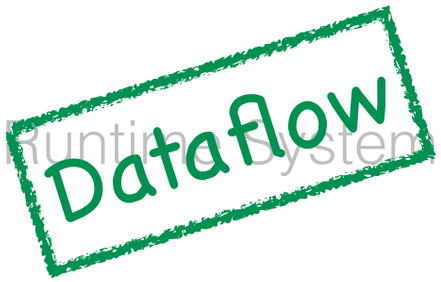
Abstraction

```
fn server(port) {
  let respond = |cnn, content, length|
                reply(cnn, compose_header(length), content);
  let (cnn, req)         = read(accept(port));
  let resource           = parse(req);
  let (content, length) = load(resource);
  respond(cnn, content, length)
}
```

Application

Programming Model/
Language

Compiler



SFP:
- Variables
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Programming Model/
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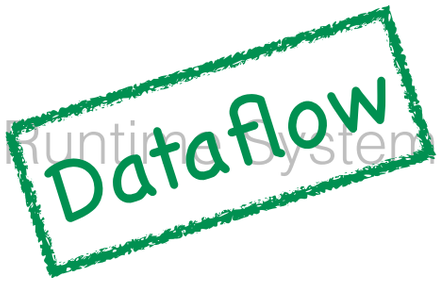
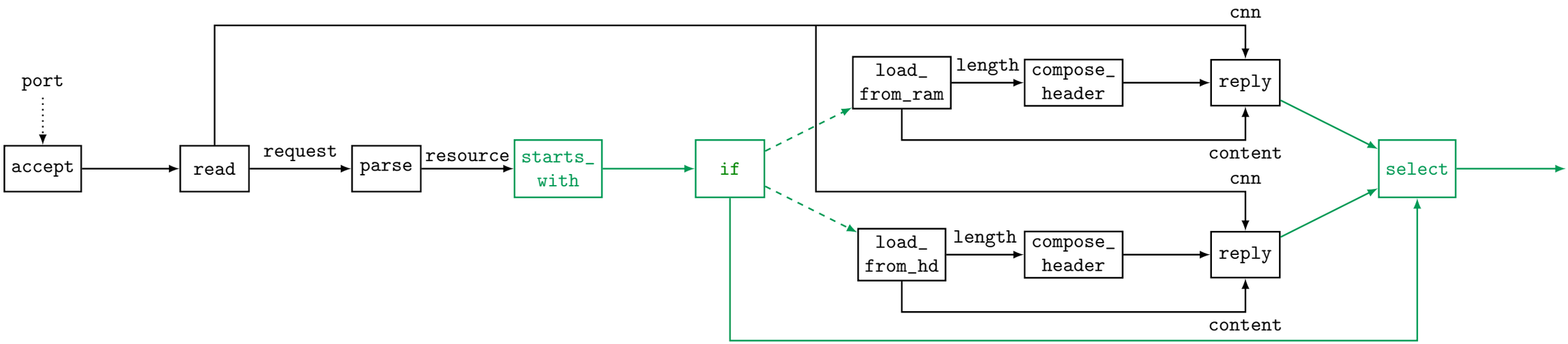


SFP:
- Variables
- Stateful Functions
- Composition
- Algorithms
- Control Flow

Control Flow




```
fn respond(cnn, content, length){
  reply(cnn, compose_header(length), content)
}

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  let (cnn, req)         = read(accept(port));
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  let (content, length) = load(resource);
  respond(cnn, content, length)
}
```

```
fn respond(cnn, content, length){
  reply(cnn, compose_header(length), content)
}

fn server(port) {
  let (cnn, req) = read(accept(port));
  let resource   = parse(req);
  if startsWith(resource, "news/") {
    let (content, length) = load_from_ram(resource);
    respond(cnn, content, length)
  } else {
    let (content, length) = load_from_hd(resource);
    reply(cnn, content, length)
  }
}
```

Programming Model/
Language

SFP:
- Variables
- Stateful Functions
- Composition
- Algorithms
- Control Flow

Compiler

Runtime System

Dataflow

Semantic Gap

```
fn server(port) {
  let cnn                = accept(port);
  let (cnn, req)         = read(cnn);
  let resource           = parse(req);
  let (content, length) = load(resource);
  reply(cnn, compose_header(length), content)
}
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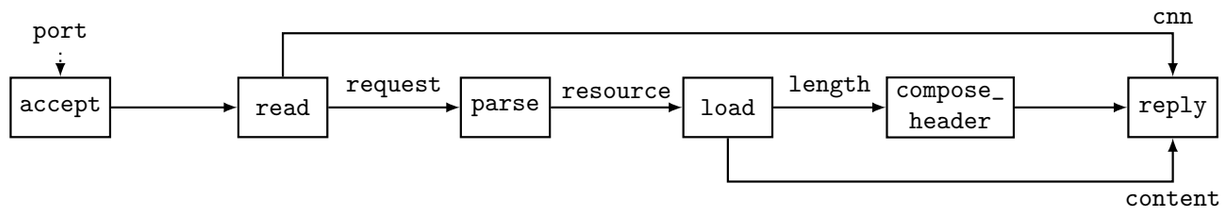

Semantic Gap

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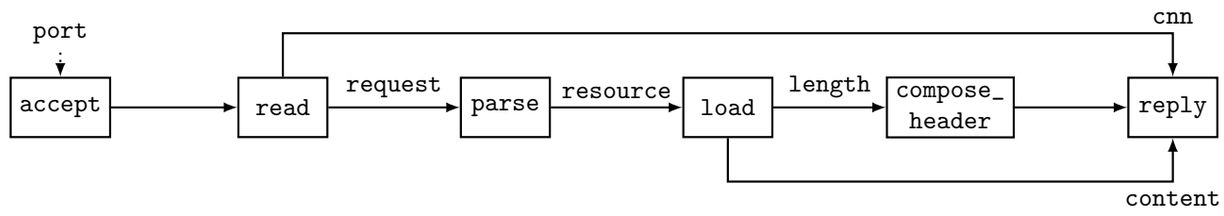

Typical PL semantics:

The **server** function executes **once** for each invocation.

Dataflow semantics:

The **server** algorithm executes **forever** for each invocation.

⇩

The **accept** node is an I/O source operator, i.e., it finishes when all requests have been exhausted!

SMap

```
fn server(port) {
  let cnn                = accept(port);
  let (cnn, req)         = read(cnn);
  let resource           = parse(req);
  let (content, length) = load(resource);
  reply(cnn, compose_header(length), content)
}
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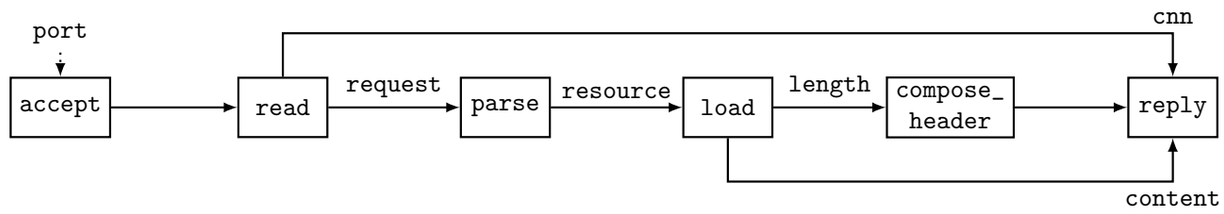

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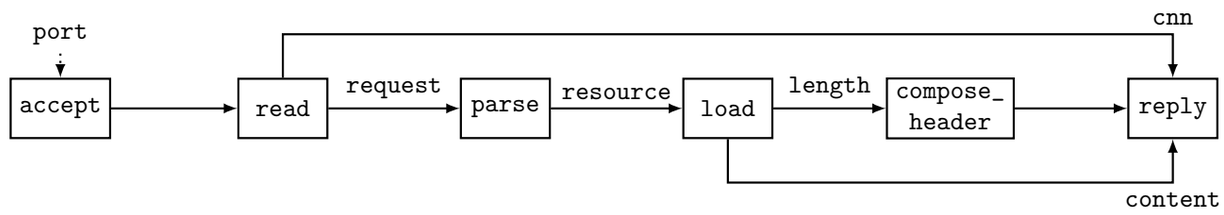

Abstract over processing:

```
fn request_handling(cnn) {
  let (cnn, req)         = read(cnn);
  let resource           = parse(req);
  let (content, length) = load(resource);
  reply(cnn, compose_header(length), content)
}

fn server(port) {
  let cnn = accept(port);
  request_handling(cnn)
}
```

SMap

```
fn server(port) {
  let cnn                = accept(port);
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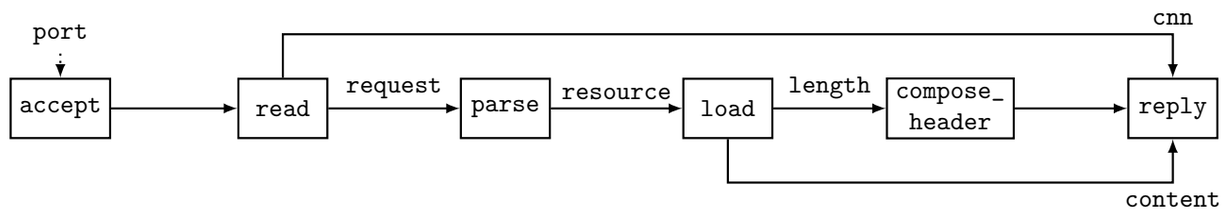

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}

fn server(port) {
  let cnn = accept(port);
  request_handling(cnn)
}
```

$I = [a_1, a_2]$

f

SMap

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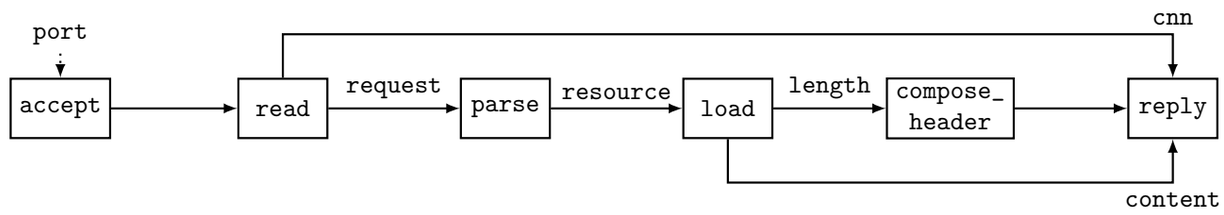

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SMap

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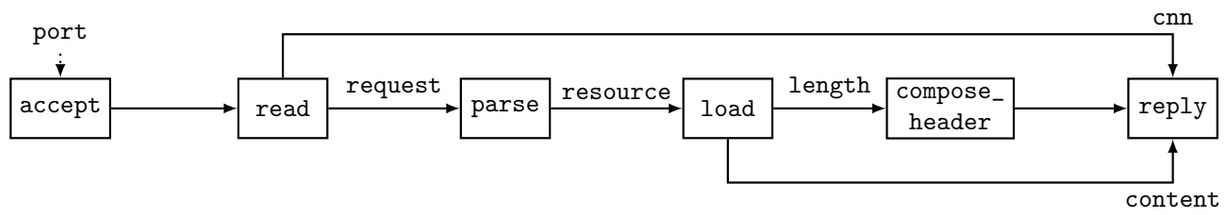

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$$I' = [b_1, b_2] = \texttt{map}(\texttt{f}, I) \quad = \quad I' = [b_1, b_2] = \texttt{smap}(\texttt{f}, I)$$

$$b_1 = \texttt{f}(a_1) \qquad (s'_f, b_1) = \texttt{f}(s_f, a_1)$$

$$b_2 = \texttt{f}(a_2) \qquad (s''_f, b_2) = \texttt{f}(s'_f, a_2)$$

SMap

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fn server(port) {
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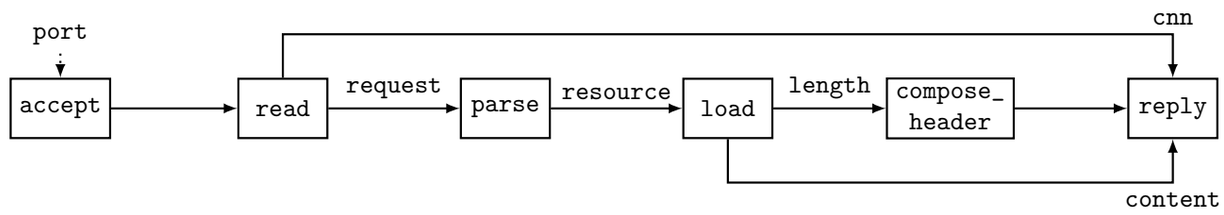

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data parallel strictly sequential

SMap

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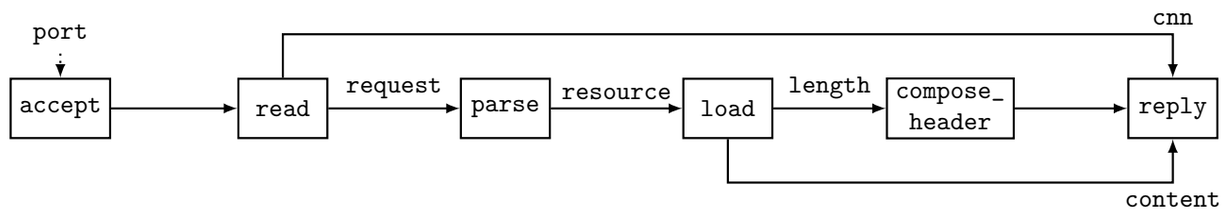

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data parallel — strictly sequential

```
fn f(a){
  let x = g(a);
  h(x)
}
```

⇨

$\texttt{f} = \texttt{h} \circ \texttt{g}$

$s_f = (s_g, s_h)$

SMap

```
fn server(port) {
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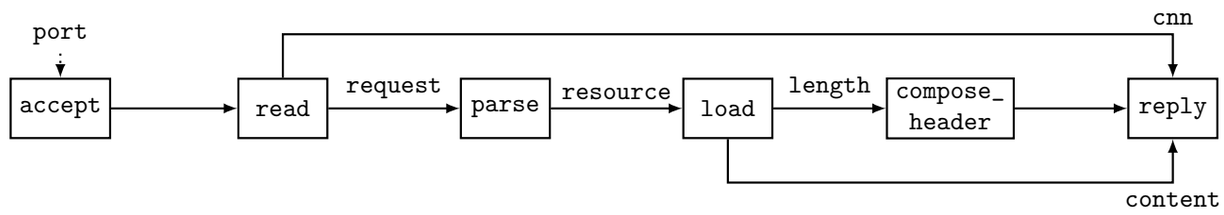

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$\texttt{f} = \texttt{h} \circ \texttt{g}$

$s_f = (s_g, s_h)$

$$(s'_g, x_1) = \texttt{g}(s_g, a_1)$$
$$(s''_g, x_2) = \texttt{g}(s'_g, a_2)$$
$$(s'_h, b_1) = \texttt{h}(s_h, x_1)$$
$$(s''_h, b_2) = \texttt{h}(s'_h, x_2)$$

data parallel strictly sequential

SMap

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```

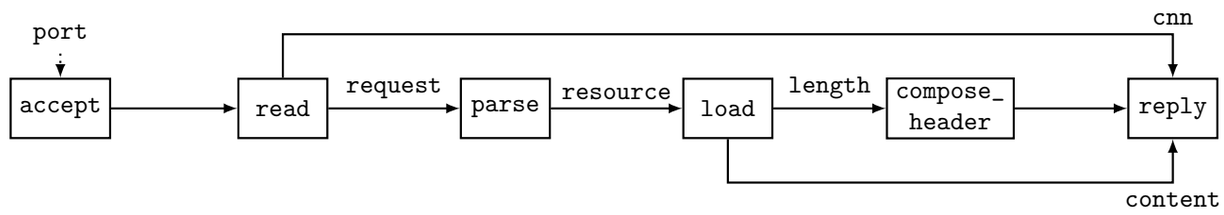

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```
fn f(a){
  let x = g(a);
  h(x)
}
```

$\texttt{f} = \texttt{h} \circ \texttt{g}$

$s_f = (s_g, s_h)$

$(s'_g, x_1) = \texttt{g}(s_g, a_1)$

$(s''_g, x_2) = \texttt{g}(s'_g, a_2)$

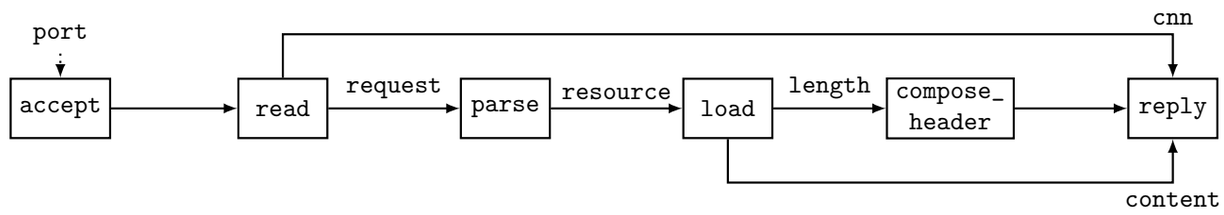
$(s'_h, b_1) = \texttt{h}(s_h, x_1)$

$(s''_h, b_2) = \texttt{h}(s'_h, x_2)$

data parallel strictly sequential

SMap

```
fn server(port) {
  let cnn                = accept(port);
  let (cnn, req)         = read(cnn);
  let resource           = parse(req);
  let (content, length) = load(resource);
  reply(cnn, compose_header(length), content)
}
```



Abstract over processing:

```
fn request_handling(cnn) {
  let (cnn, req)         = read(cnn);
  let resource           = parse(req);
  let (content, length) = load(resource);
  reply(cnn, compose_header(length), content)
}

fn server(port) {
  let cnn = accept(port);
  request_handling(cnn)
}
```

$I = [a_1, a_2]$

f

$I' = [b_1, b_2] = \texttt{map}(\texttt{f}, I)$ = $I' = [b_1, b_2] = \texttt{smap}(\texttt{f}, I)$

$b_1 = \texttt{f}(a_1)$ $\quad (s'_f, b_1) = \texttt{f}(s_f, a_1)$

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```
fn f(a){
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data parallel strictly sequential pipeline parallel

SMap

```
fn server(port) {
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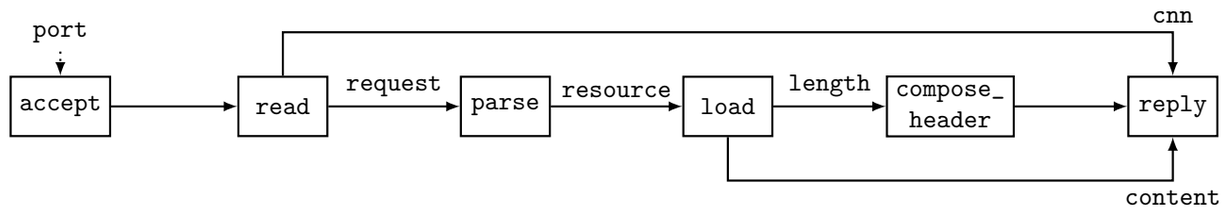

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}

fn server(port) {
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  request_handling(cnn)
}
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$I = [a_1, a_2]$

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$I' = [b_1, b_2] = \mathtt{map}(\mathtt{f}, I)$ = $I' = [b_1, b_2] = \mathtt{smap}(\mathtt{f}, I)$

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data parallel strictly sequential

Abstract over data:

Lists

- Finite
- Infinite (stream)

Generator

- Location independent

```
fn server(port) {
  let cnns:List<Cnn>   = infinite_generator(|| accept(port));
  let results:List<()> = smap(request_handling, cnns);
  ()
}
```

```
fn f(a){
  let x = g(a);
  h(x)
}
```

$\mathtt{f} = \mathtt{h} \circ \mathtt{g}$

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pipeline parallel

Allison L. Continuations implement generators and streams. The Computer Journal. 1990.

SMap

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fn server(port) {
  let cnn                = accept(port);
  let (cnn, req)         = read(cnn);
  let resource           = parse(req);
  let (content, length) = load(resource);
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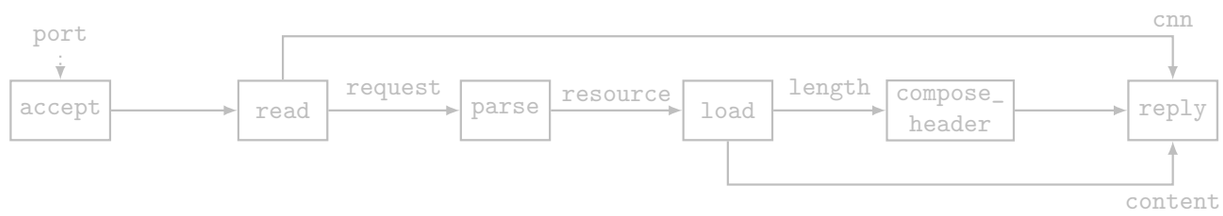


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  reply(cnn, compose_header(length), content)
}
```

```
fn server(port) {
  let cnns:List<Cnn>   = infinite_generator(|| accept(port));
  let results:List<()> = smap(request_handling, cnns);
  ()
}
```

SMap as a Loop

```
fn server(port) {
  let cnn                = accept(port);
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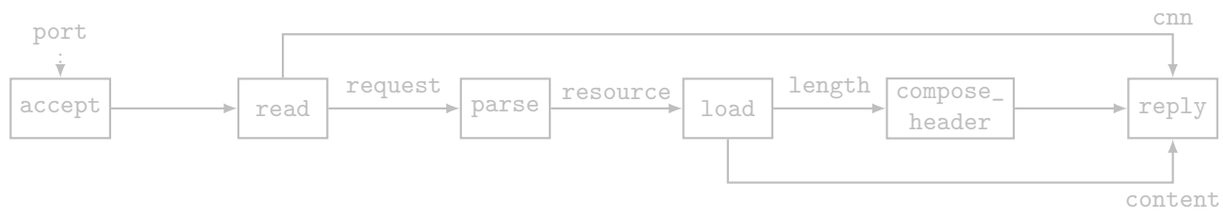
}
```

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}
```

```
fn server(port) {
  let cnns:List<Cnn>   = infinite_generator(|| accept(port));
  let results:List<()> = for cnn in cnns {
                           request_handling(cnn)
                         };
  ()
}
```

=

```
fn server(port) {
  let cnns:List<Cnn>   = infinite_generator(|| accept(port));
  let results:List<()> = smap(request_handling, cnns);
  ()
}
```

From SMap to Dataflow

```
fn server(port) {
  let cnn                = accept(port);
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  let resource           = parse(req);
  let (content, length) = load(resource);
  reply(cnn, compose_header(length), content)
}
```

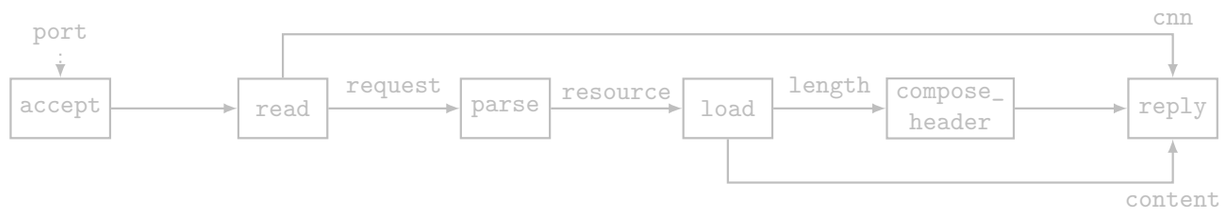


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  let results:List<()> = for cnn in cnns {
                           request_handling(cnn)
                         };
  ()
}
```

=

```
fn server(port) {
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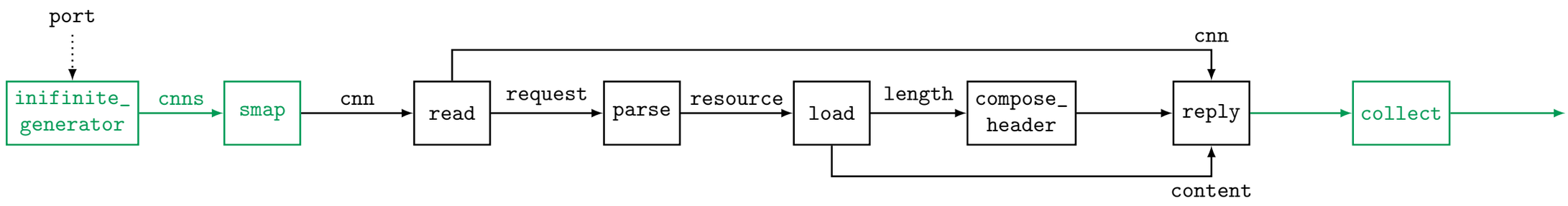
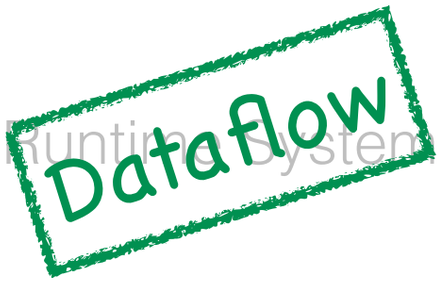
  let results:List<()> = smap(request_handling, cnns);
  ()
}
```



Programming Model/
Language

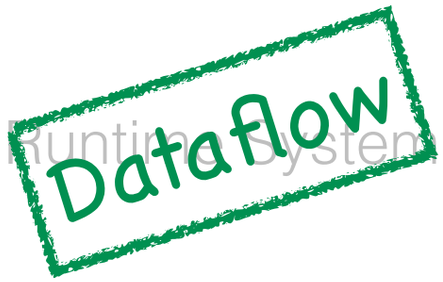
Compiler



SFP:
- Variables
- Stateful Functions
- Composition
- Algorithms
- Control Flow
- SMap

Programming Model/ Language

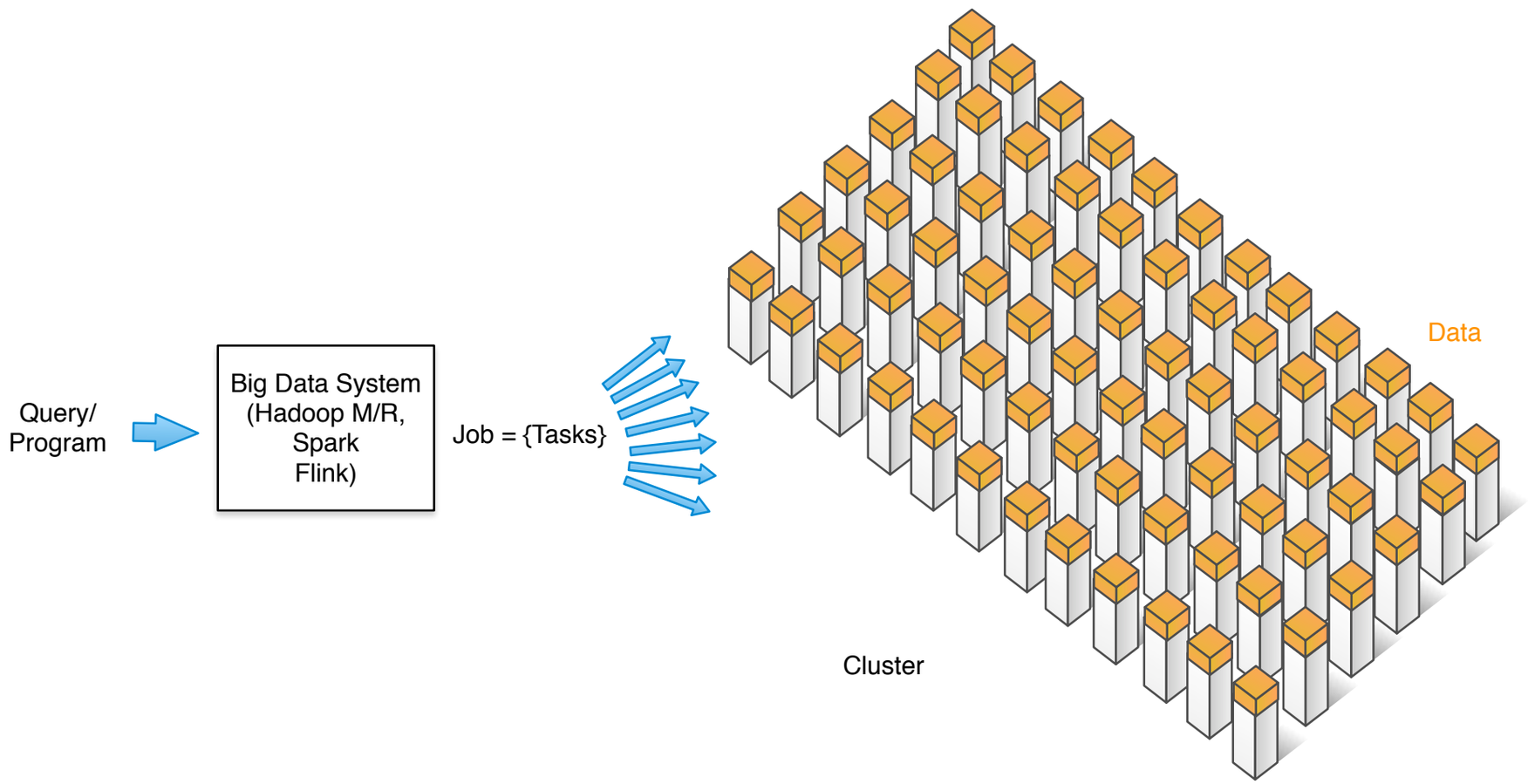
Compiler



- No concurrency abstractions.
- Practicality:
  - Integration into existing programming models (e.g., OOP)/ languages.
  - Gradual switch/ reuse of existing code base.

Big Data Systems

1. Big Data Systems (BDSs) scale with the number of cores in the cluster
2. General wisdom: The main bottleneck is I/O (disk and network)



Big Data Systems

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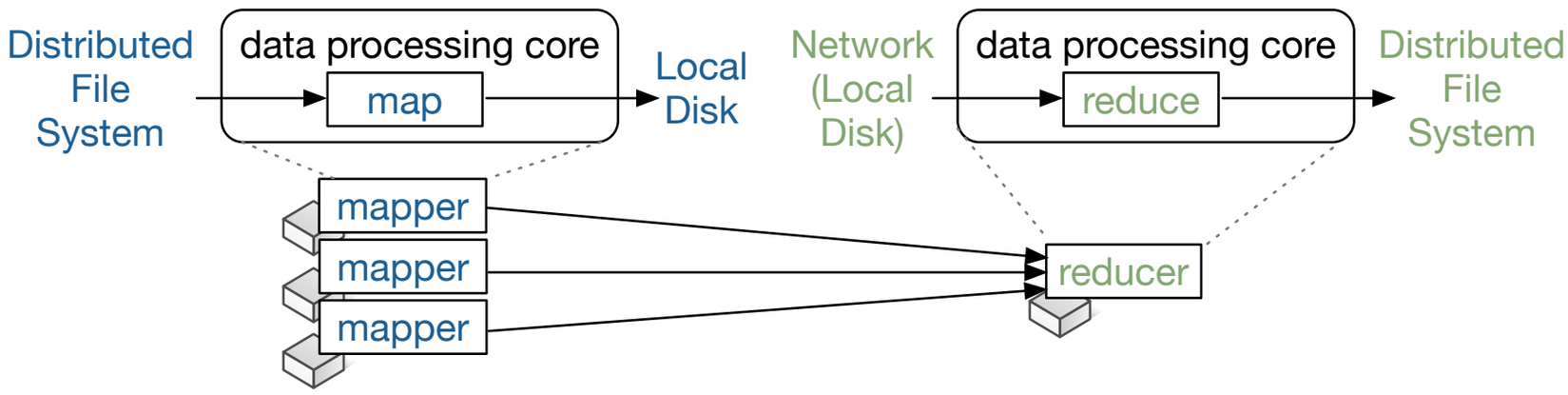

Dean J, Ghemawat S. MapReduce: simplified data processing on large clusters. Communications of the ACM. 2008.

Big Data Systems

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Jobs are CPU-bound!

WordCount, Sort		Analytics Queries (in Hive)
Simple Data Formats	vs.	Complex Data Formats (Parquet, Tables, JSON)
Uncompressed		Compressed

Kay Ousterhout, Ryan Rasti, Sylvia Ratnasamy, Scott Shenker, and Byung-Gon Chun. 2015. Making sense of performance in data analytics frameworks.(NSDI'15).

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BDS cores/data processing pipelines do not scale well on multicores!

- Local optimizations do not solve this problem.
- BDSs do not benefit from new network HW.

➡ Rewrite data processing cores!

Animesh Trivedi, Patrick Stuedi, Jonas Pfefferle, Radu Stoica, Bernard Metzler, Ioannis Koltsidas, and Nikolas Ioannou. 2016. On the [ir]relevance of network performance for data processing. (HotCloud'16).

Data Processing Cores

```
public class Mapper<KEYIN, VALUEIN,
                    KEYOUT, VALUEOUT> {
 /* The default implementation
    is the identity function. */
 protected
 void map(KEYIN key, VALUEIN value,
          Context ctxt)
  ctxt.write((KEYO
             (VALU
 }

 public
 void run(Context ctxt) {
  while (ctxt.nextKeyValue())
    map(ctxt.getCurrentKey(),
        ctxt.getCurrentValue(),
        ctxt);
 }}
```

(a) Hadoop

```
private[spark] class
ShuffleMapTask(partitionId: Int,
               partition: Partition)
 extends Task[MapStatus] {

 override
 def runTask(ctxt: TaskContext)
         partitionId, ctxt)
   writer.write(
    rdd.iterator(partition, ctxt)
       .asInstanceOf[
        Iterator[_<:Product2[Any, Any]]])
   writer.stop(success = true).get}}
```

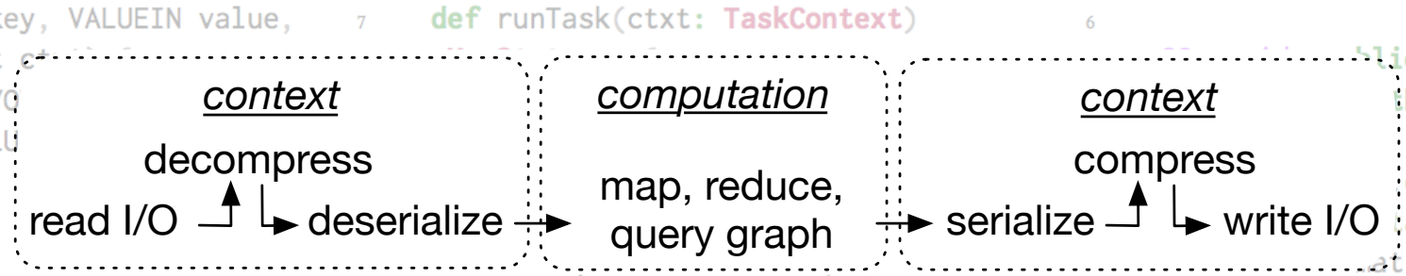
(b) Spark

```
public class DataSourceTask<OT>
 extends AbstractInvokable {
 private
  InputFormat<OT, InputSplit> format;
 private Collector<OT> output;

                                  lic
                          throws Exception {

   createInstance();
   askCanceled &&
     t.reachedEnd()) {
    OT returned;
    if((returned =
          format.nextRecord(reuse))
        != null)
      output.collect(returned);
 }}}
```

(c) Flink



Rewriting Hadoop Map/Reduce

```
fn output_side(writer, key, value) {
  output(writer, key, value)
}

fn compute_and_output(mapper, writer, split) {
  let (line, content) = split;
  let kv_pairs = hmr_map(mapper, line, content);
  for kv_pair in kv_pairs {
    let (k, v) = kv_pair;
    output_side(writer, k, v)
  }
}

fn coarse(reader: org.apache.hadoop.mapreduce.Mapper$Context,
          mapper: org.apache.hadoop.mapreduce.Mapper,
          writer: org.apache.hadoop.mapreduce.Mapper$Context) {
  let splits = finite_generator(|| load_split(reader),
                                || has_more_data(reader));
  for split in splits {
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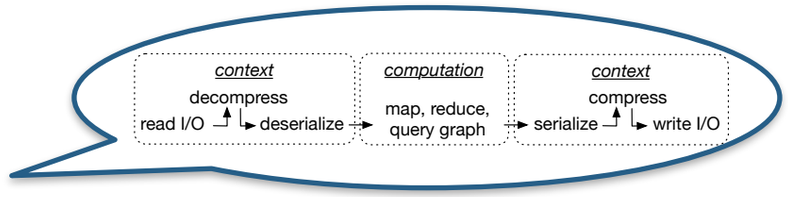

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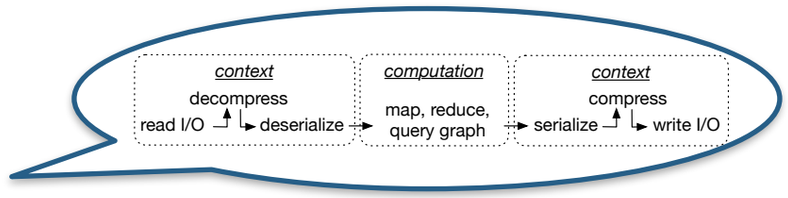

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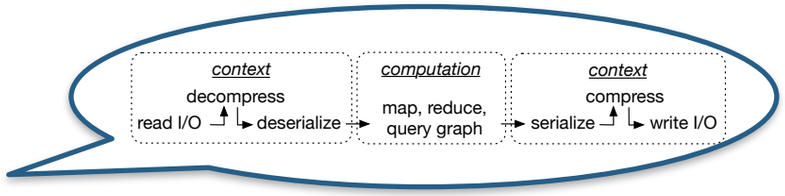
```

writer.write(key, value)



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```
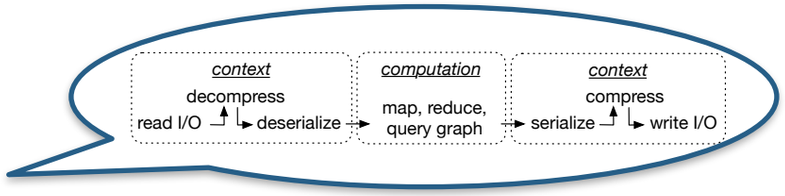
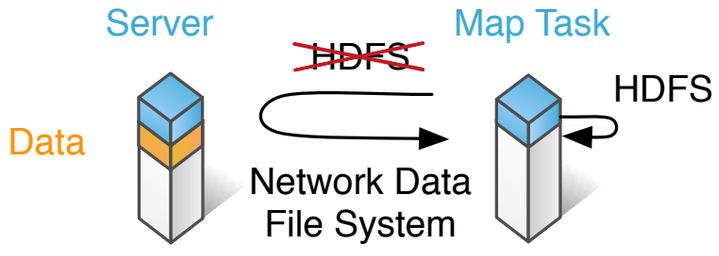

writer.write(key, value)

4 variants:

- Coarse (C)
- Coarse Input Fine Output (CIFO)
- Fine Input Coarse Output (FICO)
- Fine (F)



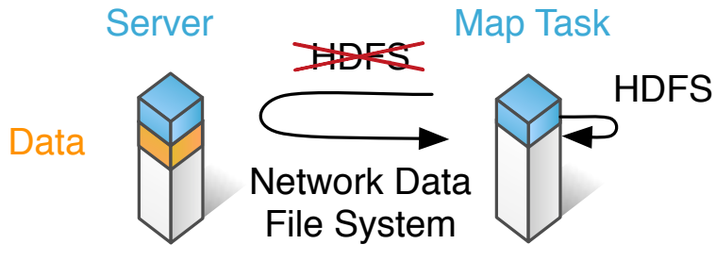
Evaluation



Almost the same setup as for a reduce task!

- SequenceFile
- JSON
- Snappy, LZO
- TPC-H Parts table

Throughput Analysis



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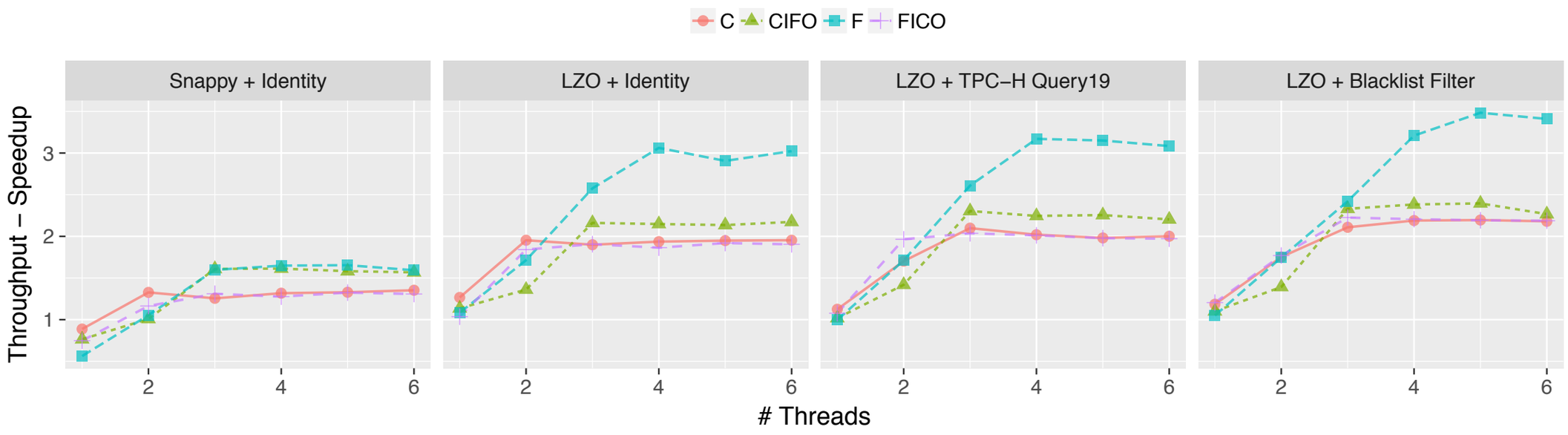


Speedup of up to 3.5x for compute-intensive configurations!

Programming Model/
Language

SFP:
- Variables
- Stateful Functions
- Composition
- Algorithms
- Control Flow
- SMap

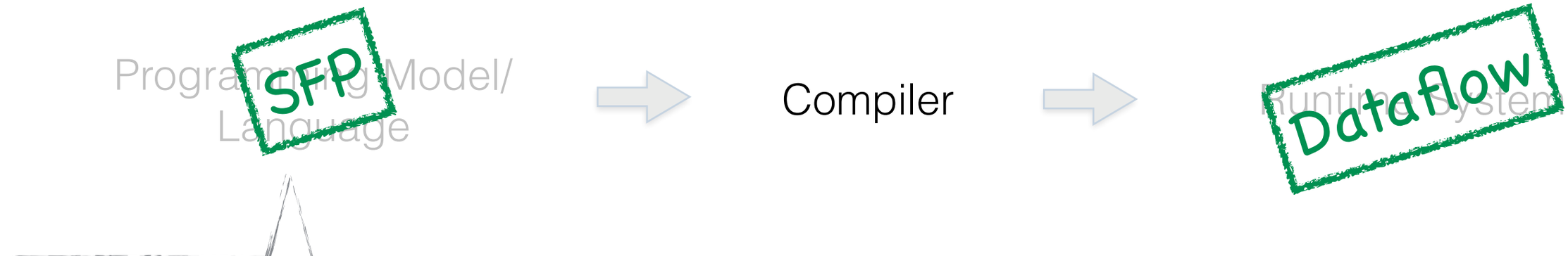
Compiler

Runtime System

Dataflow

Sebastian Ertel, Christof Fetzer, and Pascal Felber. 2015. Ohua: Implicit Dataflow Programming for Concurrent Systems. In Proceedings of the Principles and Practices of Programming on The Java Platform (PPPJ '15). ACM.

Sebastian Ertel, Justus Adam, and Jeronimo Castrillon. 2018. Supporting Fine-grained Dataflow Parallelism in Big Data Systems. In Proceedings of the 9th International Workshop on Programming Models and Applications for Multicores and Manycores (PMAM'18). ACM.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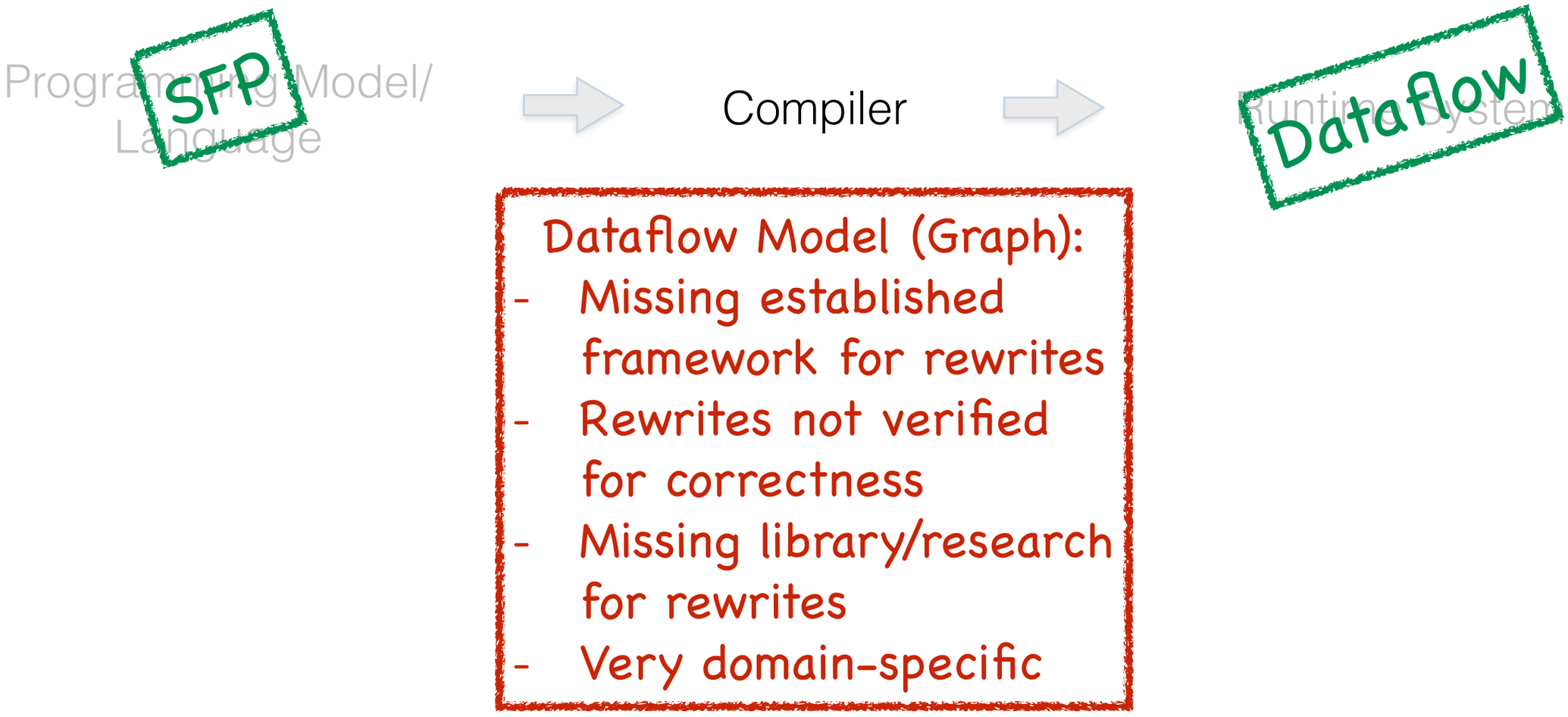
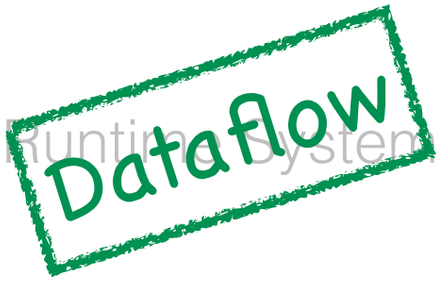
• Integration into existing programming models (e.g., OOP)/ languages.
• Gradual switch/ reuse of existing code base.


SFP
Programming Model/
Language
Compiler
Runtime System
Dataflow
Dataflow Model (Graph):
- Missing established framework for rewrites
- Rewrites not verified for correctness
- Missing library/research for rewrites
- Very domain-specific

PL/Compiler Co-Design

Programming Model/ Language

Compiler



SFP:

- Variables
- Stateful Functions
- Composition
- Algorithms
- Control Flow
- SMap

J. Backus. Can programming be liberated from the von neumann style?: A functional style and its algebra of programs. Commun. ACM, 1978.

Barendregt, Hendrik Pieter. "Functional programming and lambda calculus." *Formal models and semantics*. Elsevier, 1990.

PL/Compiler Co-Design

Programming Model/ Language → Compiler → Runtime System

SFP:
- Variables
- Stateful Functions
- Composition
- Algorithms
- Control Flow
- SMap

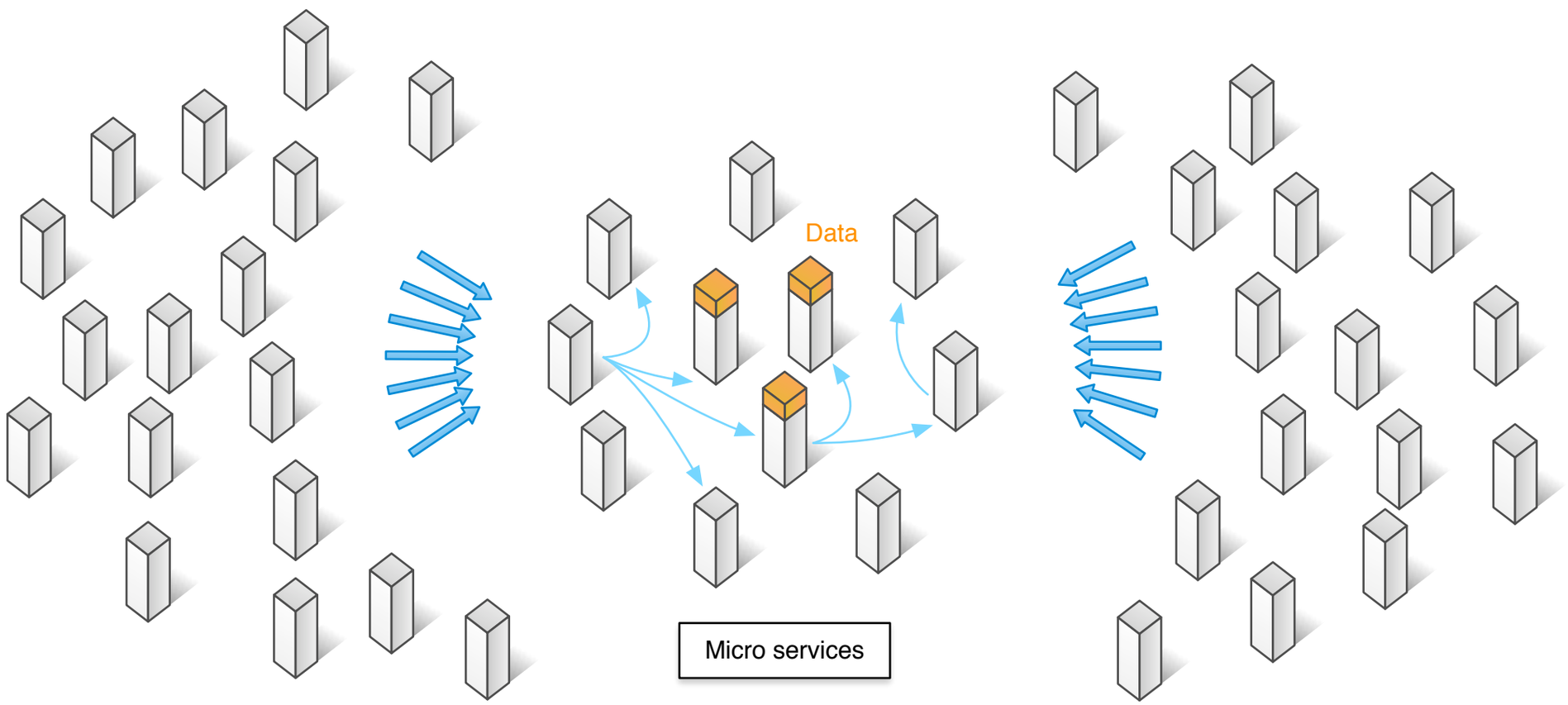
Lambda calculus:
- Variables
- Abstraction
- Application

Dataflow

J. Backus. Can programming be liberated from the von neumann style?: A functional style and its algebra of programs. Commun. ACM, 1978.

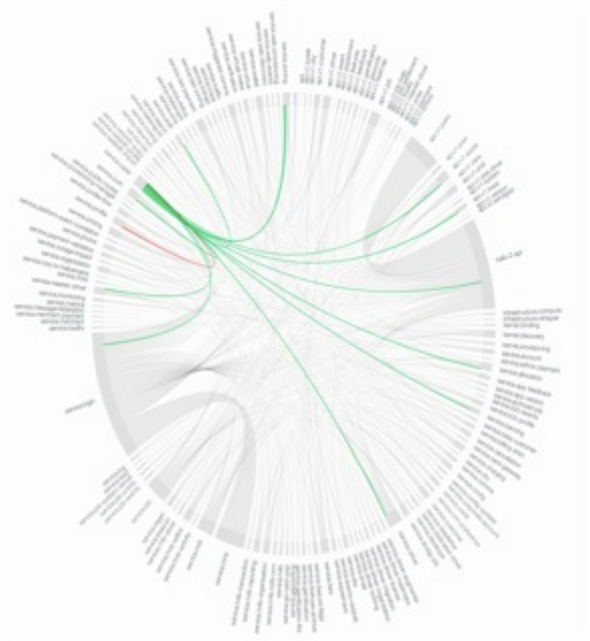
Barendregt, Hendrik Pieter. "Functional programming and lambda calculus." *Formal models and semantics*. Elsevier, 1990.

Microservice Architectures

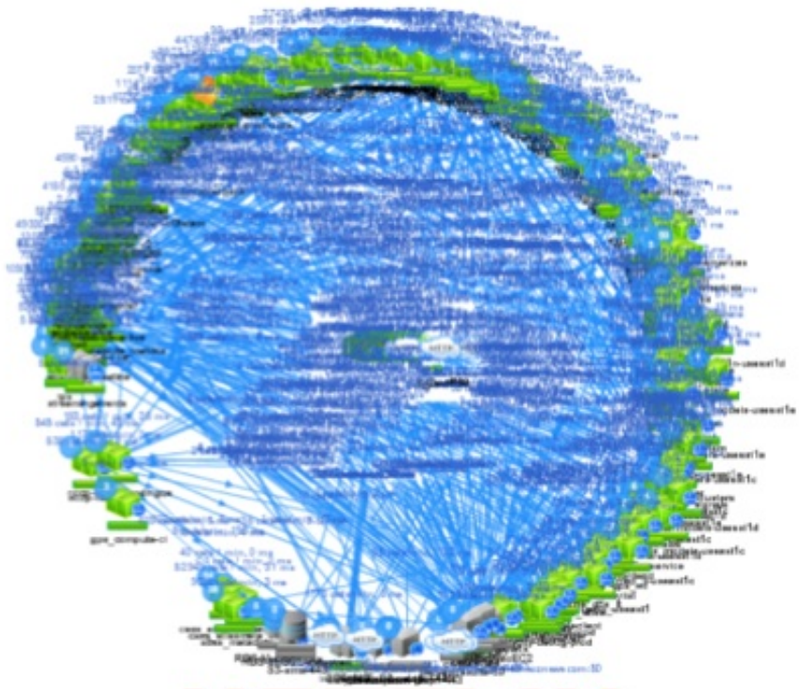


Redefining the Death Star

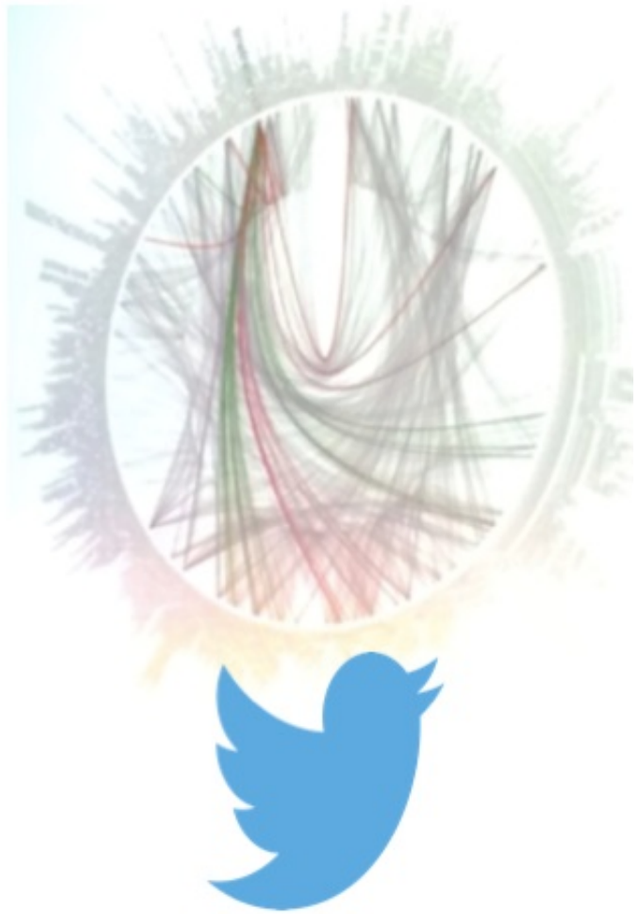
450 microservices



500+ microservices

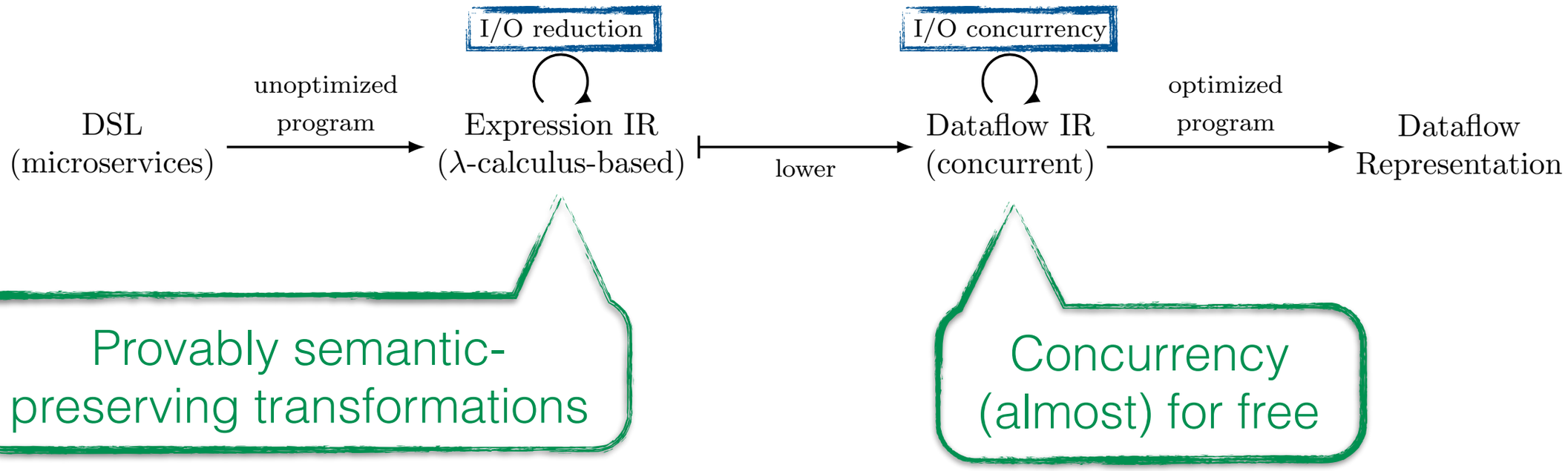


500+ microservices

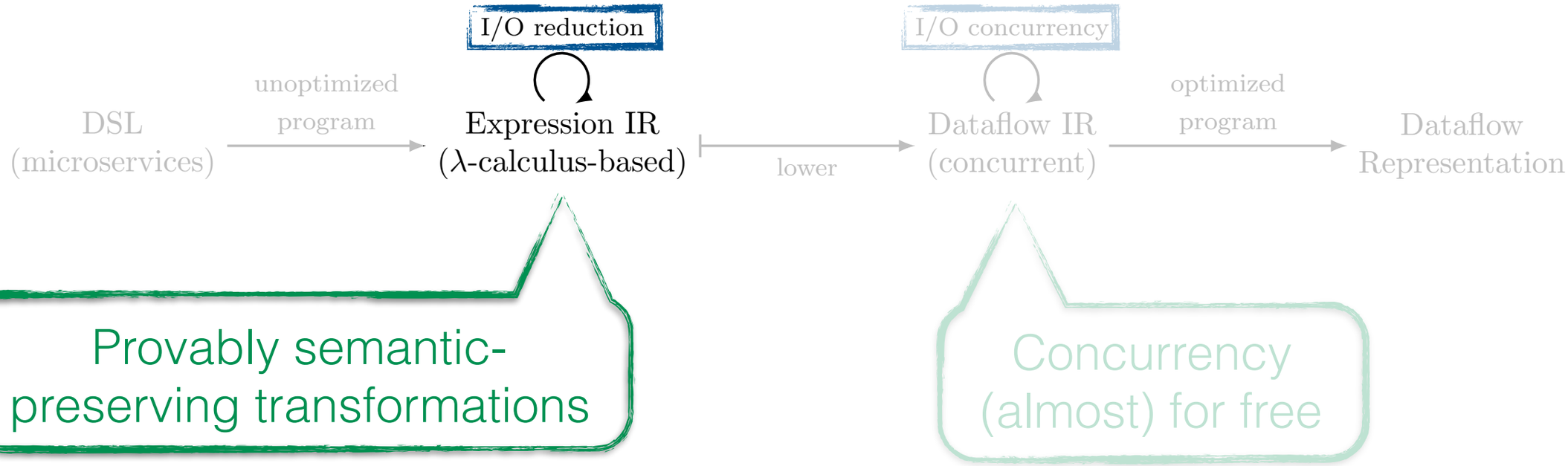


Source:
Netflix: http://www.slideshare.net/BruceWong3/the-case-for-chaos
Twitter: https://twitter.com/adrianco/status/441883572618948608
Hail-o: https://sudo.hailoapp.com/services/2015/03/09/journey-into-a-microservice-world-part-3/

Compiler


I/O reduction
I/O concurrency
unoptimized program
optimized program
DSL (microservices)
Expression IR (λ-calculus-based)
lower
Dataflow IR (concurrent)
Dataflow Representation
Provably semantic-preserving transformations
Concurrency (almost) for free

Compiler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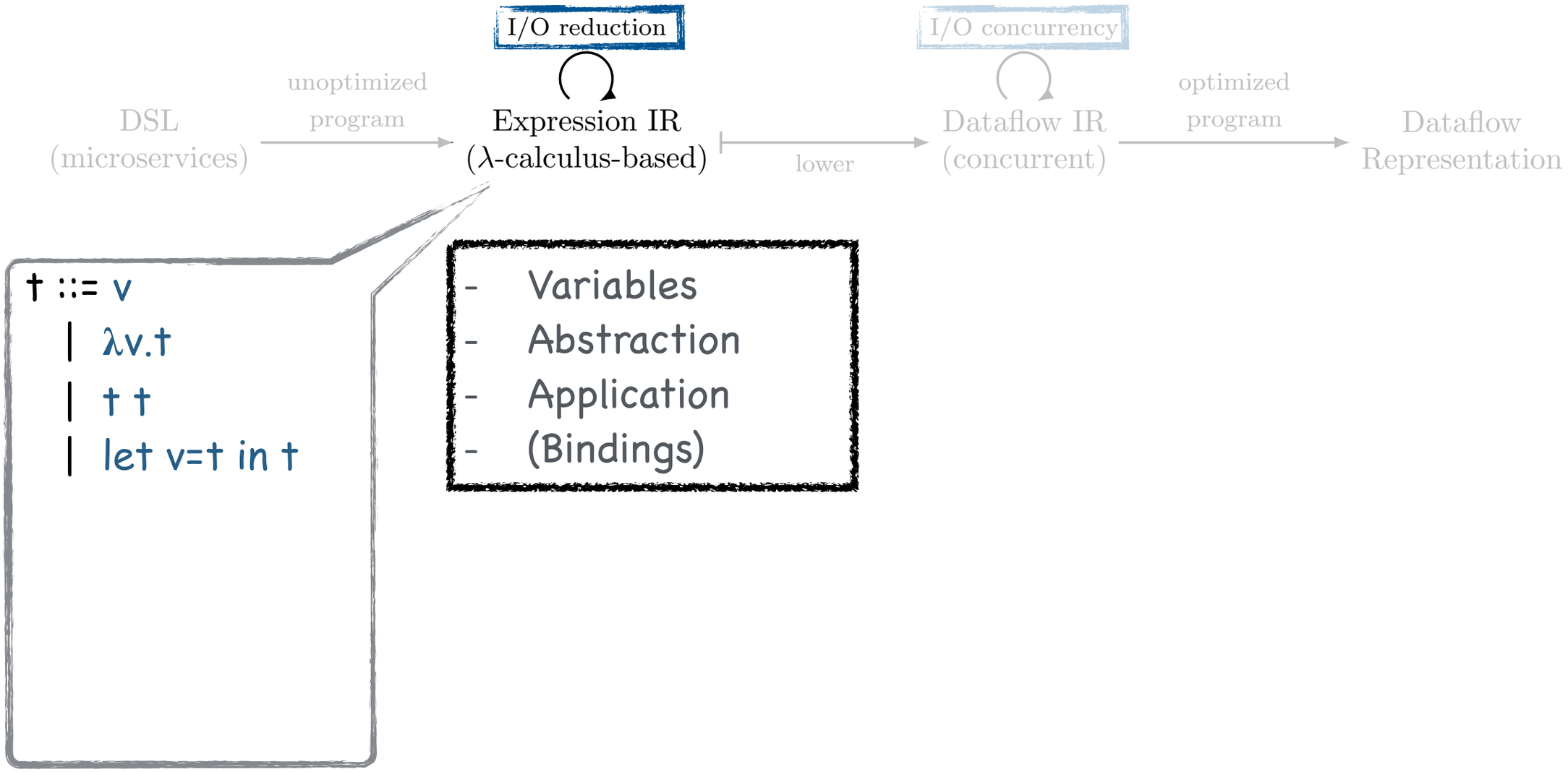
Dataflow
Representation
Provably semantic-
preserving transformations
Concurrency
(almost) for free

Foundation: Call-by-need Lambda Calculus

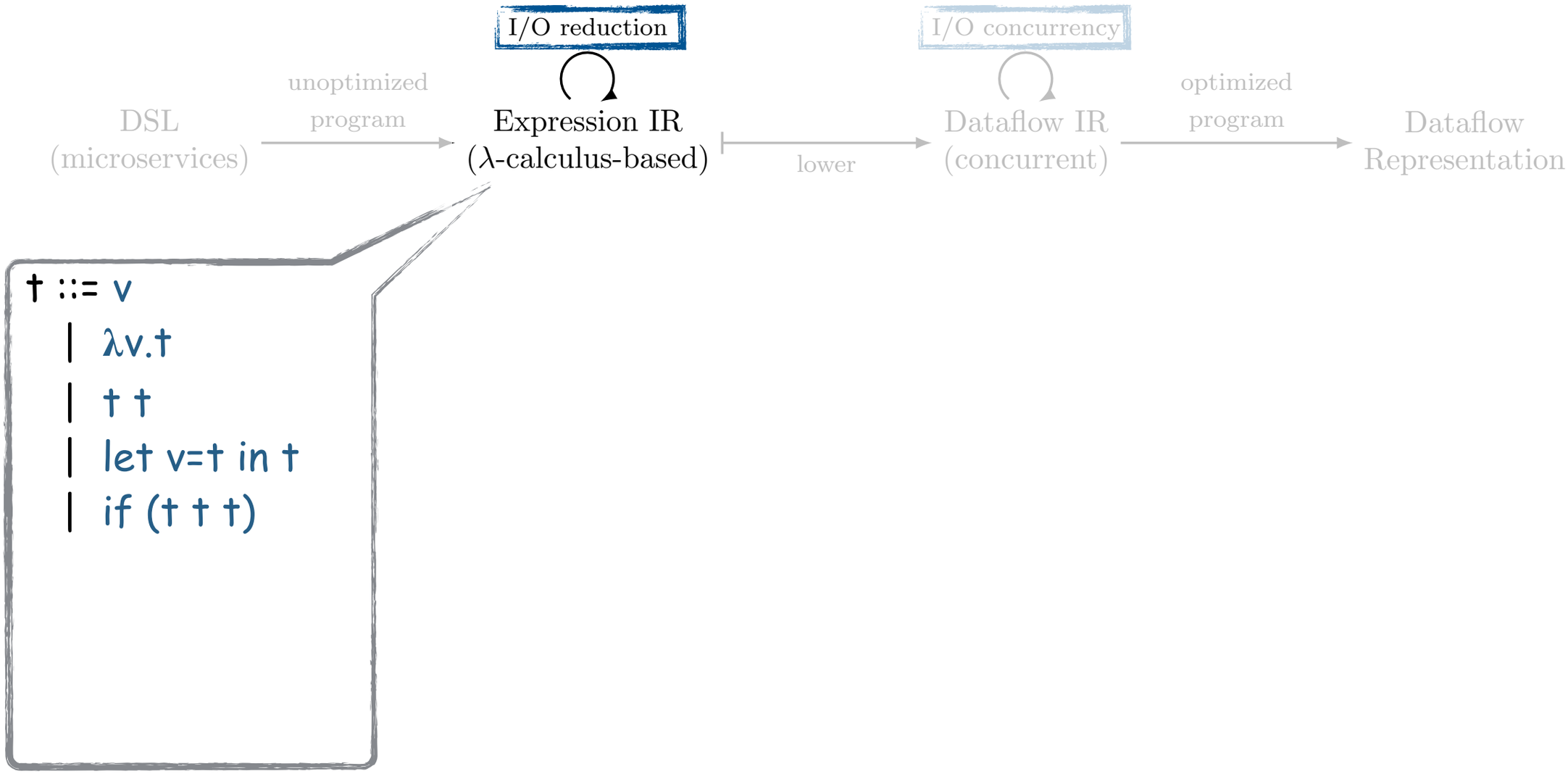


Ariola ZM, Felleisen M. The call-by-need lambda calculus. Journal of functional programming. 1997.

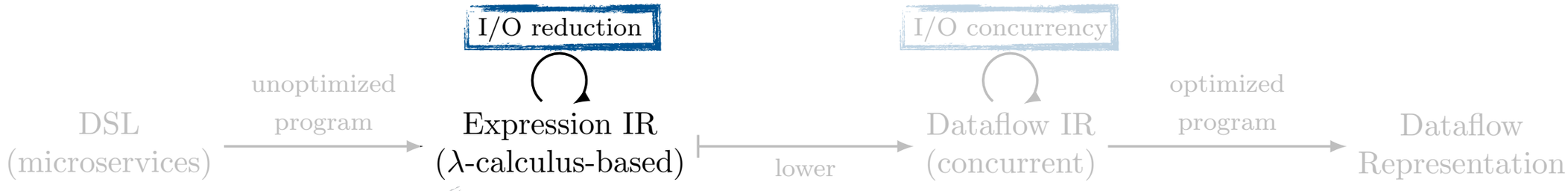
Maraist J, Odersky M, Wadler P. The call-by-need lambda calculus. Journal of functional programming. 1998.

Chang S, Felleisen M. The call-by-need lambda calculus, revisited. In European Symposium on Programming 2012. Springer.

Foundation: Call-by-need Lambda Calculus



Domain-specific Aspects



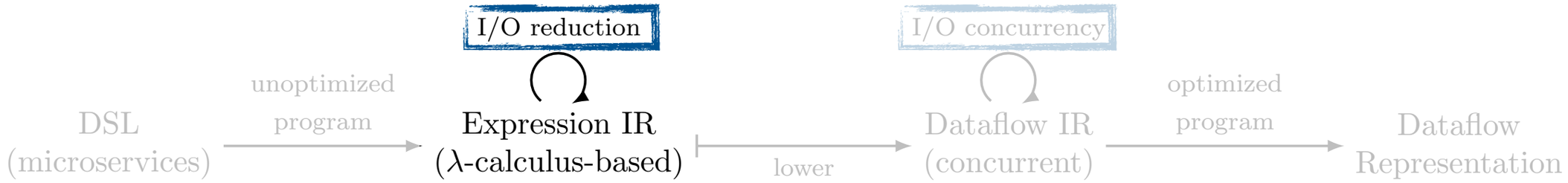

```
t ::= v
    | λv.t
    | t t
    | let v=t in t
    | if (t t t)
    | ff_f(x_1 ... x_n)
    | io(x)

map(λv.t [v_1 ... v_n])
```

- stateless/stateful functions
- I/O (read) request

- SMap

I/O Transformations

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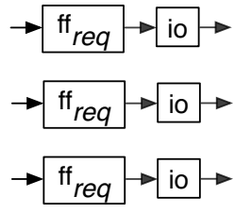
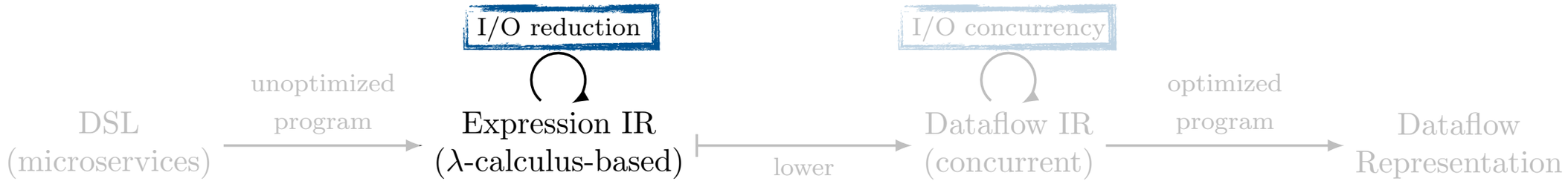
- Grouping <u>independent</u> I/O calls:



I/O Transformations

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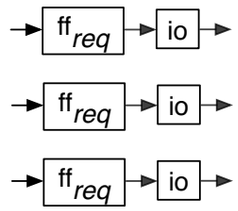

Remember SMap

$$(s'_g, x_1) = \mathtt{g}(s_g, a_1)$$
$$(s''_g, x_2) = \mathtt{g}(s'_g, a_2)$$
$$(s'_h, b_1) = \mathtt{h}(s_h, x_1)$$
$$(s''_h, b_2) = \mathtt{h}(s'_h, x_2)$$

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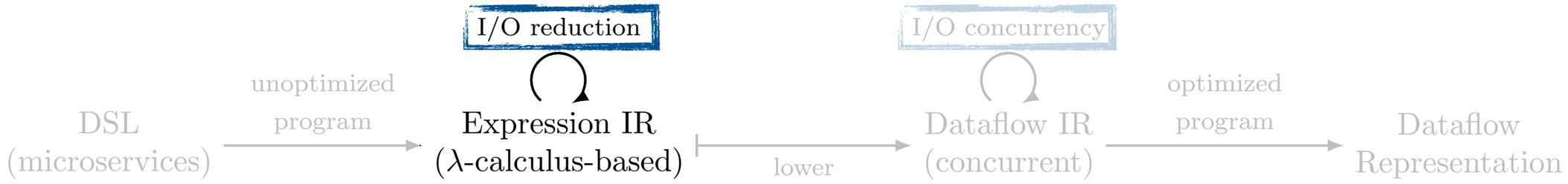
$$(s''_h, b_2) = \mathtt{h}(s'_h, x_2)$$

pipeline parallel

I/O Transformations

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    | io(x)

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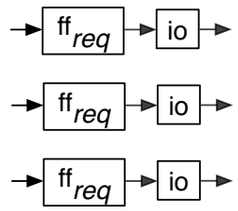
```

- Grouping <u>independent</u> I/O calls:



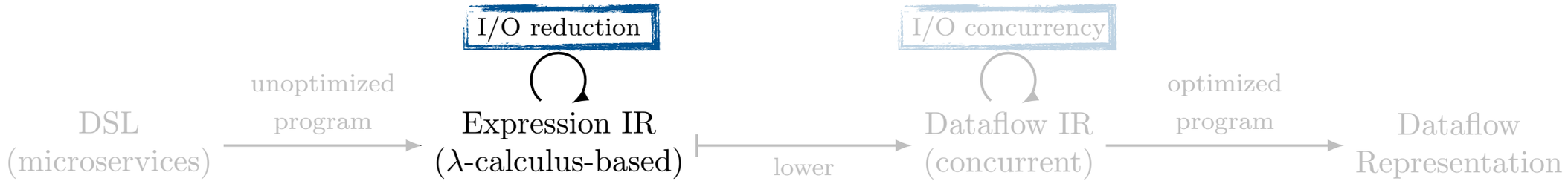
Let-floating

$$\texttt{smap}(\texttt{f}, [a_1, a_2]) = \begin{array}{l} \texttt{let } (s'_g, x_1) = \texttt{g}(s_g, a_1) \texttt{ in} \\ \texttt{let } (s''_g, x_2) = \texttt{g}(s'_g, a_2) \texttt{ in} \\ \texttt{let } (s'_h, b_1) = \texttt{h}(s_h, x_1) \texttt{ in} \\ \texttt{let } (s''_h, b_2) = \texttt{h}(s'_h, x_2) \texttt{ in} \\ [b_1, b_2] \end{array} = \begin{array}{l} \texttt{let } (s'_g, x_1) = \texttt{g}(s_g, a_1) \texttt{ in} \\ \texttt{let } (s'_h, b_1) = \texttt{h}(s_h, x_1) \texttt{ in} \\ \texttt{let } (s''_g, x_2) = \texttt{g}(s'_g, a_2) \texttt{ in} \\ \texttt{let } (s''_h, b_2) = \texttt{h}(s'_h, x_2) \texttt{ in} \\ [b_1, b_2] \end{array}$$

pipeline **parallel**

Peyton Jones S, Partain W, Santos A. Let-floating: moving bindings to give faster programs. In ACM SIGPLAN Notices 1996. ACM.

I/O Transformations

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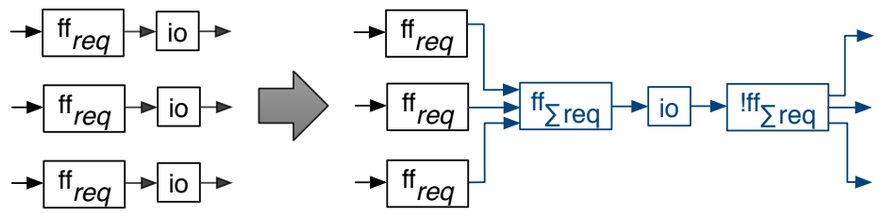
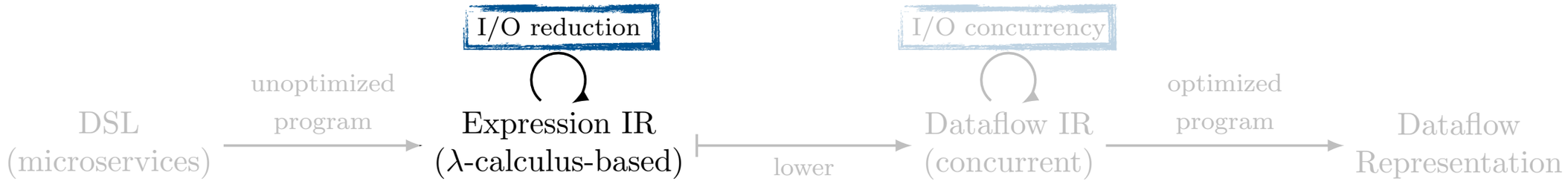
- Grouping <u>independent</u> I/O calls:



I/O Transformations

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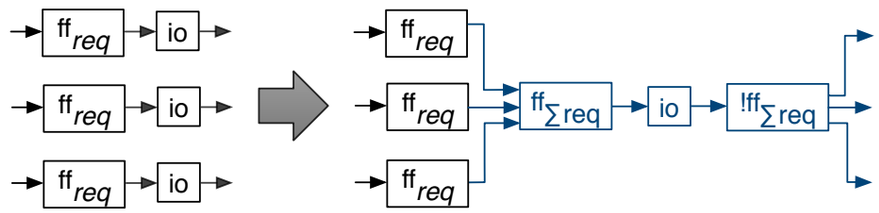
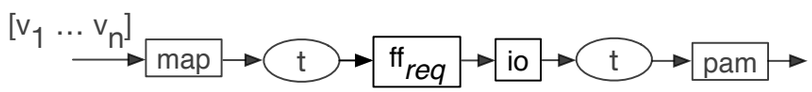
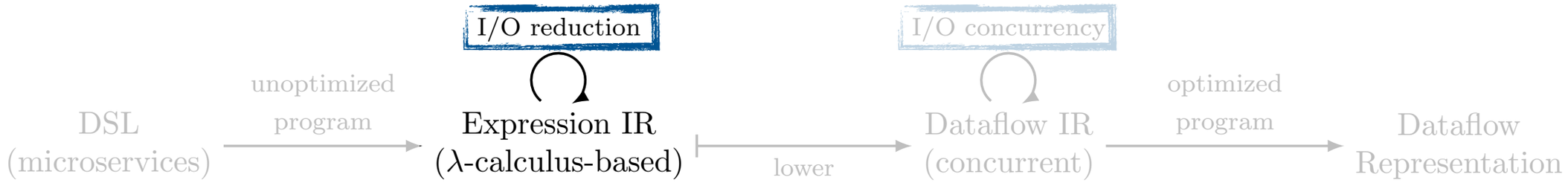


- Lifting I/O calls:



I/O Transformations

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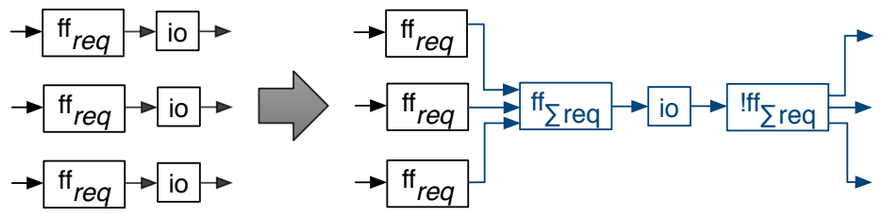
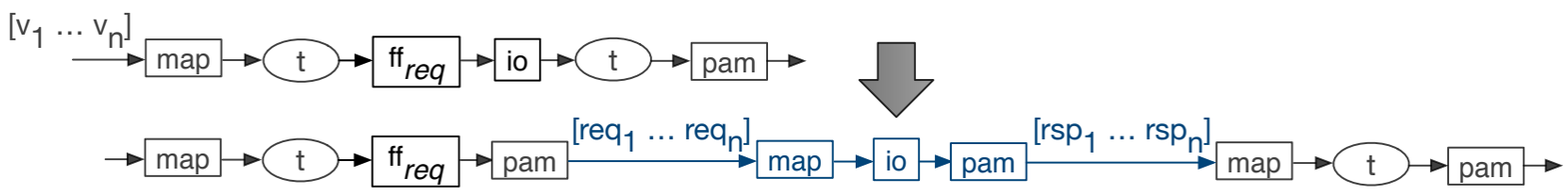
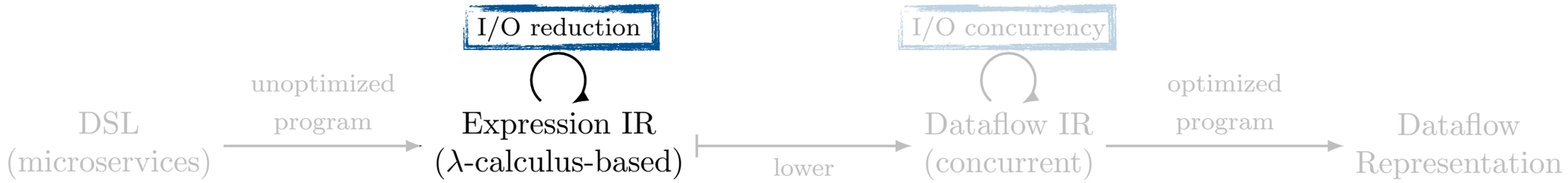


- Lifting I/O calls:



I/O Transformations

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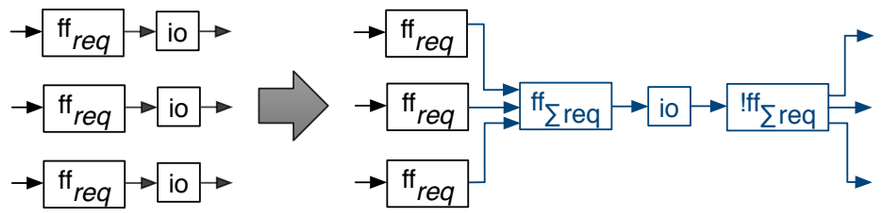

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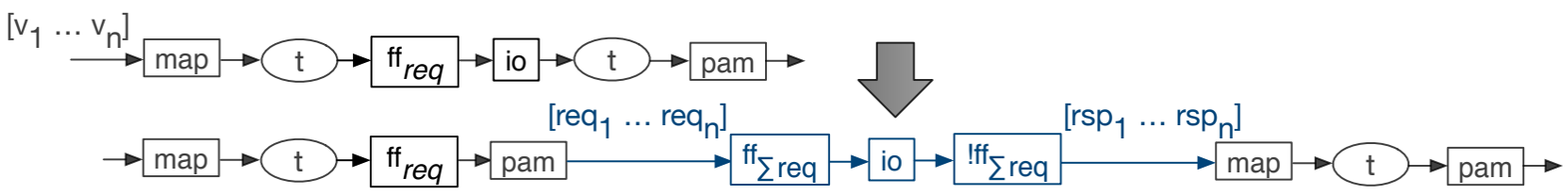
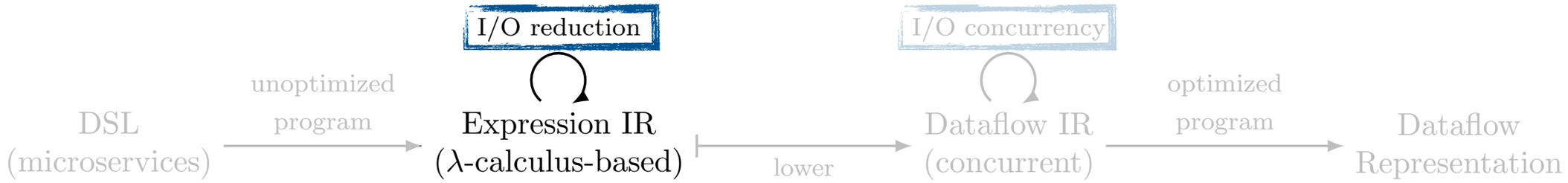


I/O Transformations

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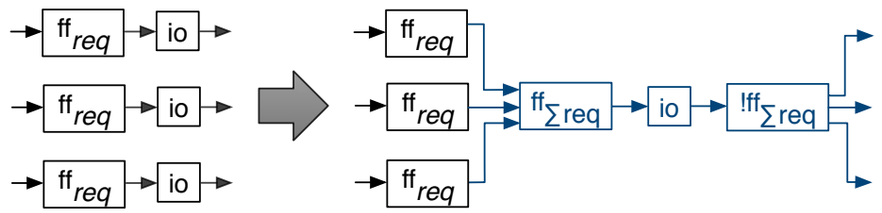

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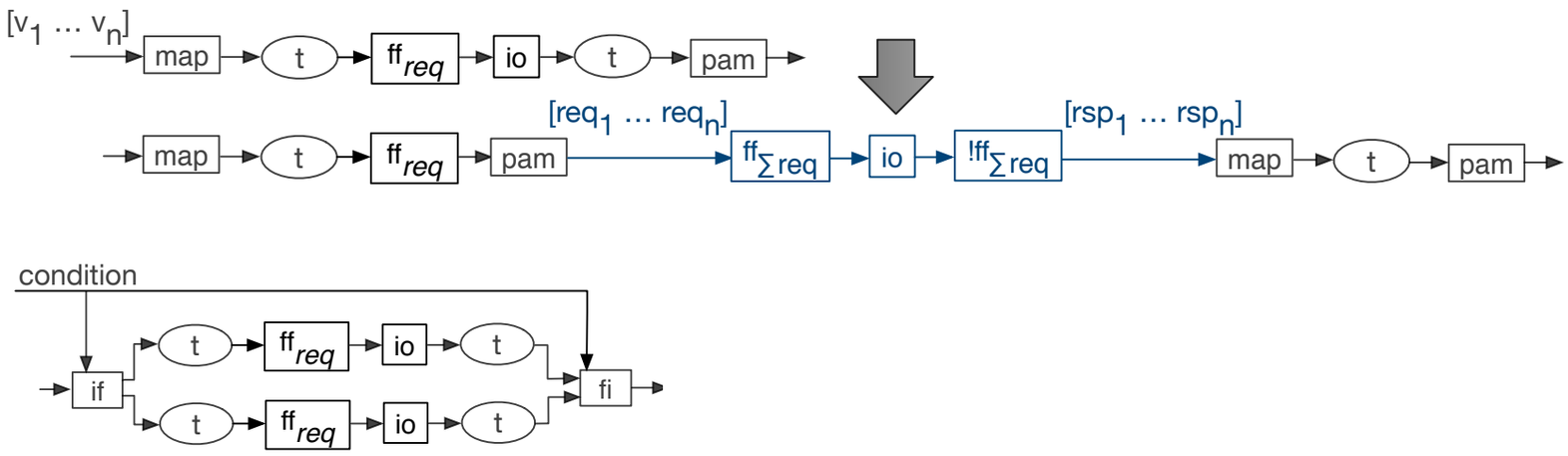
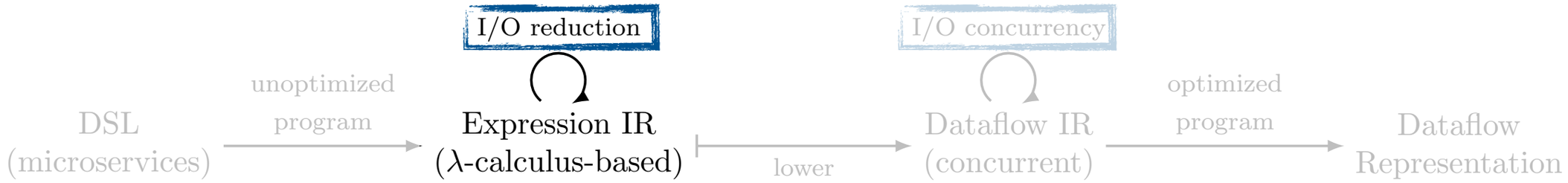


I/O Transformations

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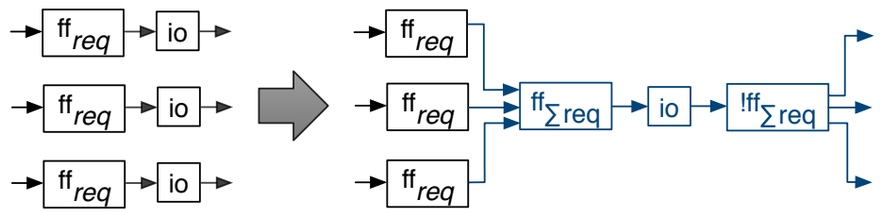

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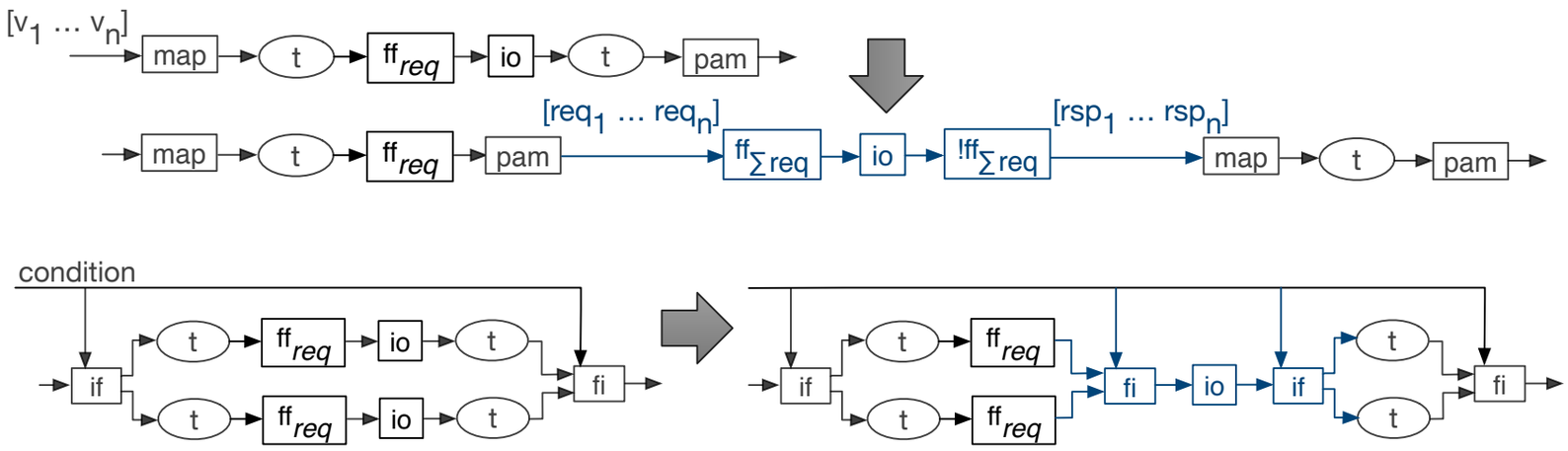
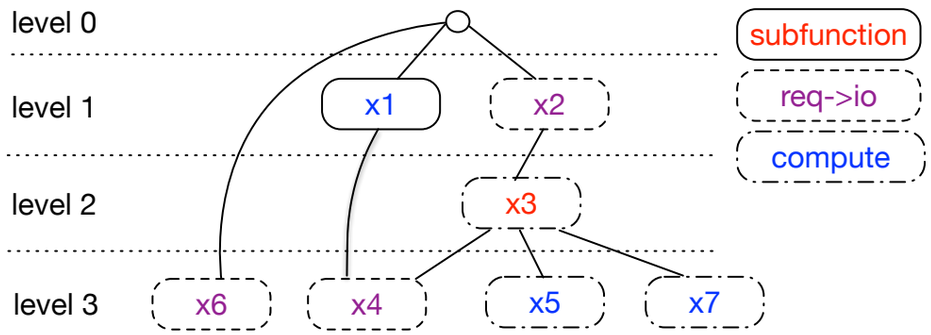


Evaluation

Level-Graphs:

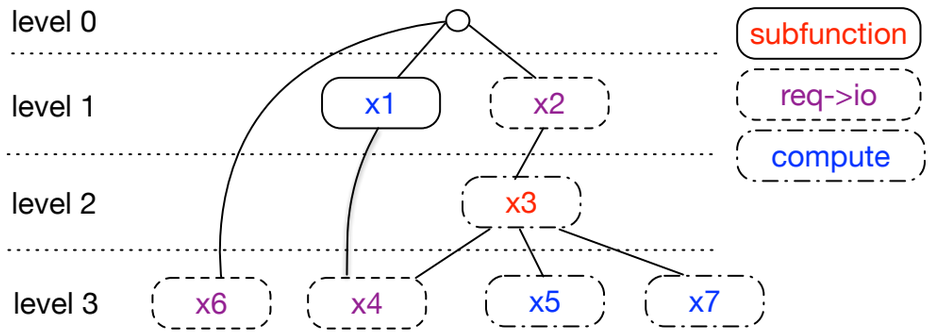


Programs:

Andrés Goens, Sebastian Ertel, Justus Adam, and Jeronimo Castrillon. 2018. Level Graphs: Generating Benchmarks for Concurrency Optimizations in Compilers. MULTIPROG'18.

Evaluation

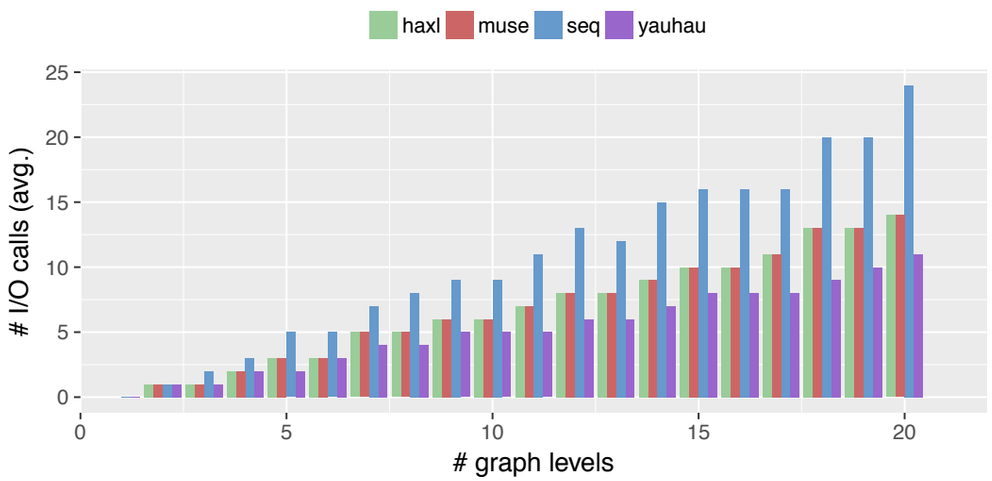
Level-Graphs:

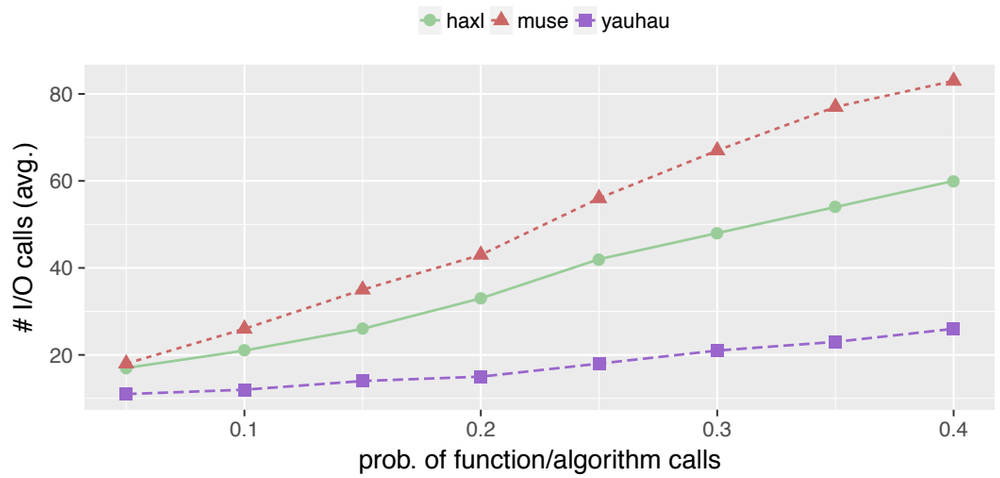


serialize

Programs:

- Haxl
- Muse
- Seq
- Ÿauhau





Simon Marlow, Louis Brandy, Jonathan Coens, and Jon Purdy. 2014. There is no fork: an abstraction for efficient, concurrent, and concise data access. ICFP '14.

Alexey Kachayev. 2015. Reinventing Haxl: Efficient, Concurrent and Concise Data Access. Presentation at EuroClojure 2015.

Programming Model/ Language

SFP

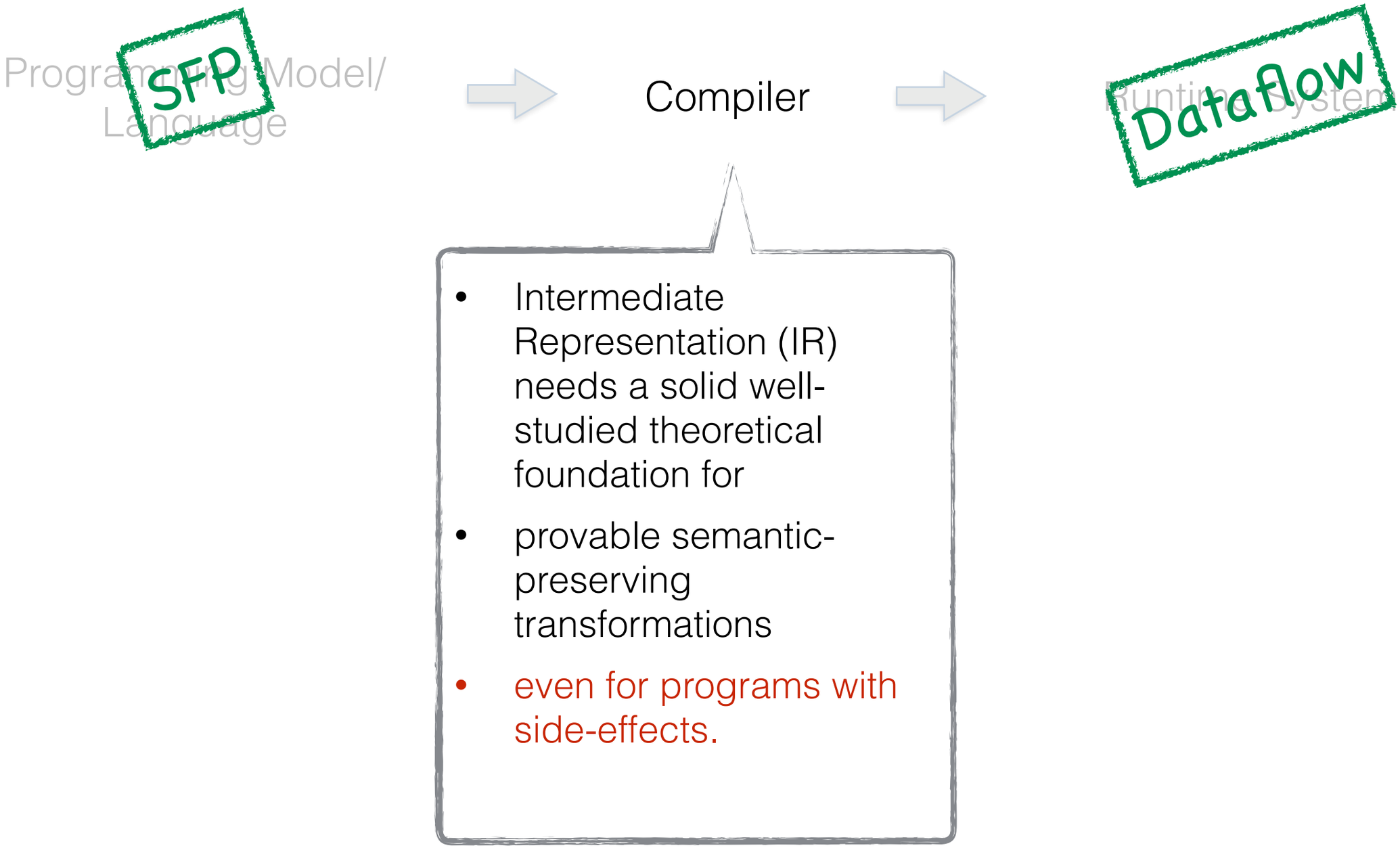
Compiler

Runtime System

Dataflow

Lambda calculus:
- Variables
- Abstraction
- Application

Sebastian Ertel, Andrés Goens, Justus Adam, and Jeronimo Castrillon. 2018. Compiling for concise code and efficient I/O. In Proceedings of the 27th International Conference on Compiler Construction (CC 2018). ACM.


Programming Model/
Language
SFP
Compiler
Runtime System
Dataflow
• Intermediate Representation (IR) needs a solid well-studied theoretical foundation for
• provable semantic-preserving transformations
• even for programs with side-effects.

Programming Model/
Language

SFP:
- Variables
- Stateful Functions
- Composition
- Algorithms
- Conditionals
- SMap

Compiler

Lambda calculus:
- Variables
- Abstraction
- Application
- Combinators

Dataflow
Runtime System

Stateful Functions

?

```
class FileLoad extends Filter {

  private Channel<String> in, out;

  public void work() {
    // explicit channel control
    String resource = in.take();
    String contents = load(resource);
    out.put(contents);
  }

  private Map<String, String> cache = new HashMap<>();

  private String load(String resource){
    String content = null;
    if(!cache.containsKey(resource)){
      content = new String(
          Files.readAllBytes(Paths.get(resource))
        );
      cache.put(resource,content);
      // cache eviction emitted for brevity
    } else {
      content = cache.get(resource);
    }
    return content;
  }

}
```

State encapsulation

```
class FileLoad {
  Map<String, String> cache = new HashMap<>();

  String load(String resource) {
    String contents = null;
    // load file data from disk or cache (omitted)
    return contents;
  }
}
```



```
struct FileLoad {
   cache : HashMap,
};

impl FileLoad {
  fn load(&self, resource:String) -> String {
    let contents : String = {
    // load file data from disk or cache (omitted)
    };
    contents
  }
}
```

```
char* load(char* resource) {
  static GHashTable* cache = g_hash_table_new();
  char* contents = NULL;
  // load file data from disk or cache (omitted)
  return contents;
}
```

Foundations of Stateful Functions

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State Threads:

```
load :: String -> State (HashMap String String)
                        String
load :: String -> ST (MHashMap s String String)
                     String
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$$f_{st} = (a, s) \to (b, s)$$

Composition:

$$f = a \to b$$
$$g = b \to c$$
$$g \circ f = a \to c$$

$$f_{st} = (a, s_f) \to (b, s_f)$$
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SMap:

- Formal analysis on determinism and deadlocks.
- Not only **map**s but also **fold**s!
- Not only pipeline parallelism but also task-level and data parallelism!

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$$g_{st} \circ f_{st} = ?$$

```
fn map_reduce() {
  let stateG = init_G();
  for data in list {
    let x = f(data);
    stateG.g(x)
  };
  stateG
}
```

Sebastian Ertel, Justus Adam, Norman A. Rink, Andrés Goens, and Jeronimo Castrillon. 2019. STCLang: state thread composition as a foundation for monadic dataflow parallelism. In Proceedings of the 12th ACM SIGPLAN International Symposium on Haskell (Haskell 2019). ACM.

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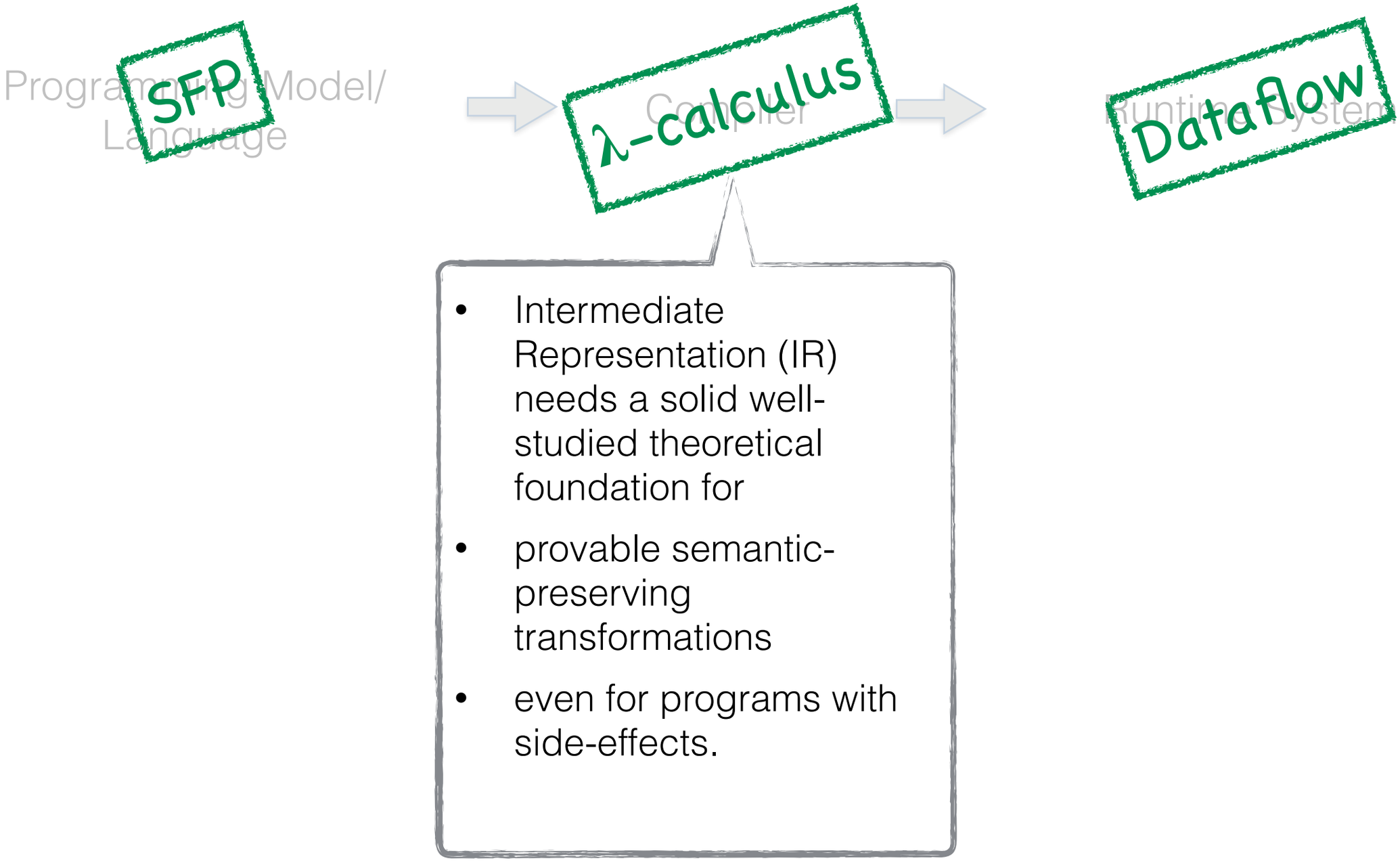
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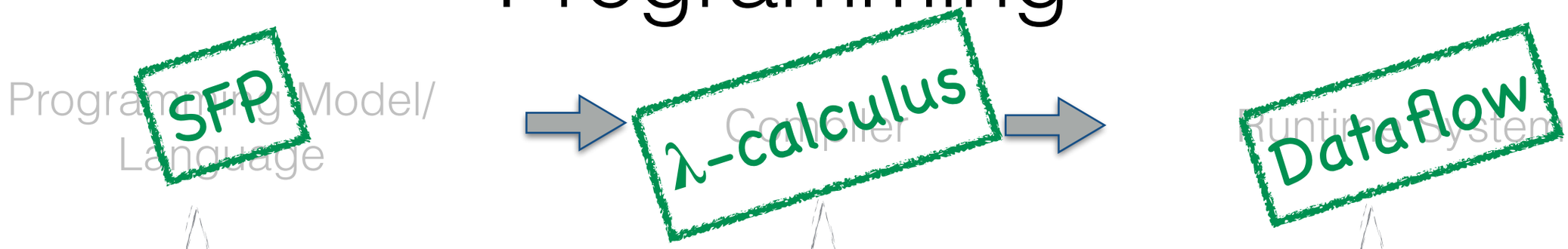
Ingredients for Implicit Parallel Programming



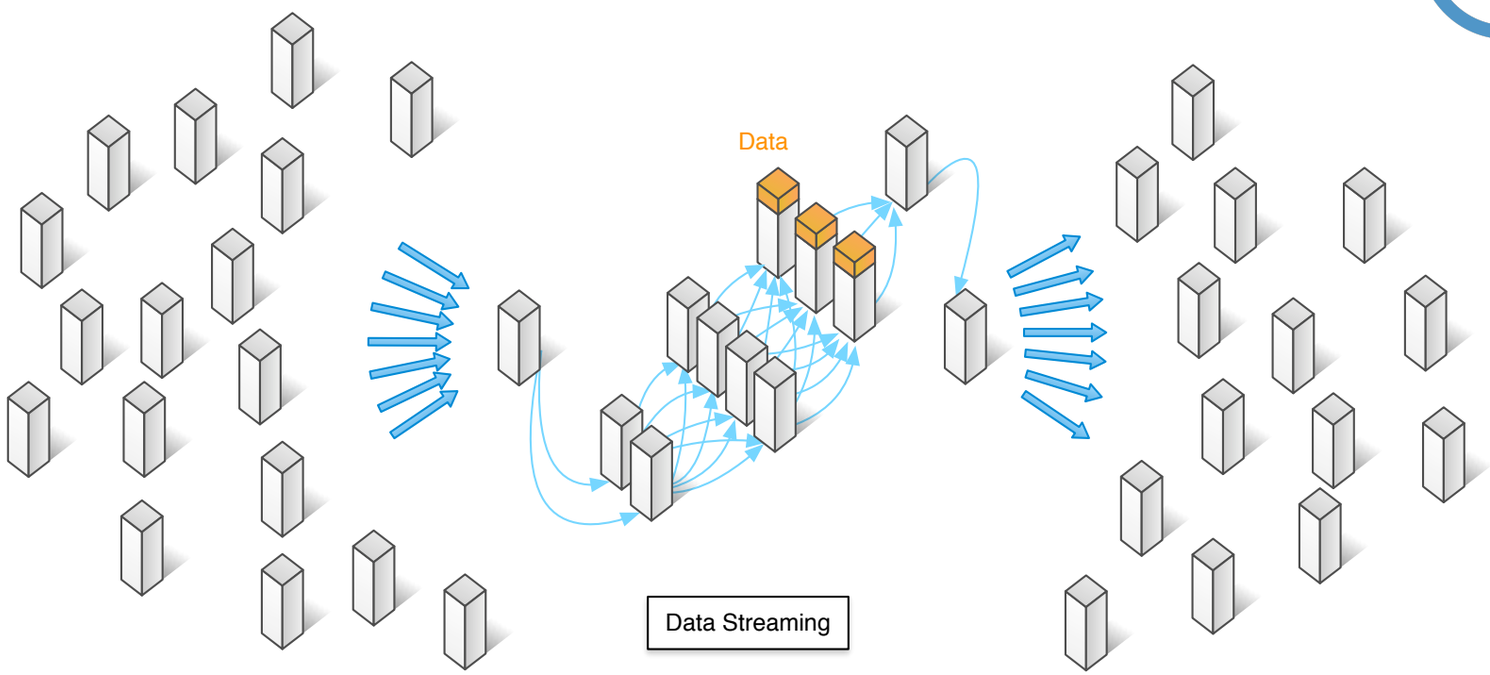
- No concurrency abstractions.
- Practicality:
  - Integration into existing programming models (e.g., OOP)/ languages.
  - Gradual switch/ reuse of existing code base.

- Intermediate Representation (IR) needs a solid well-studied theoretical foundation for
- provable semantic-preserving transformations
- even for programs with side-effects.

- Flexible/dynamic runtime representation.
- Efficient parallel execution of independent computations.
- Deterministic execution.
- Concurrent I/O.

Changing the Game

- Functional Reactive Programming (FRP) based on stateful functions.
- FRP instead of streams for big data systems.
  https://github.com/ohua-dev/stc-lang



- Current Main Focus: Rust integration ➪ Safety
  https://github.com/ohua-dev/ohua-rust-runtime
- STM alternative.
- User-defined functions and NoSQL (in Noria).

Thanks for your attention!

https://ohua-dev.github.io/