ÆMINIUM

Freeing Programmers from the Shackles of Sequentiality

Thesis Proposal Talk
Sven Stork

Committee

Jonathan Aldrich (CMU)	Paulo Marques (UC)
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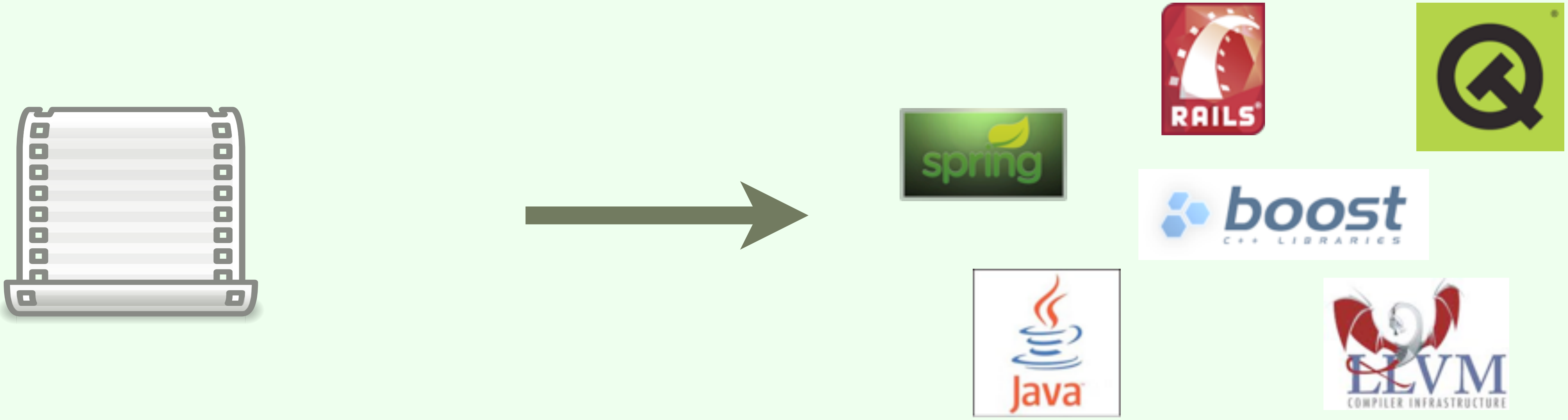
William Scherlis (CMU)	Marco Viera (UC)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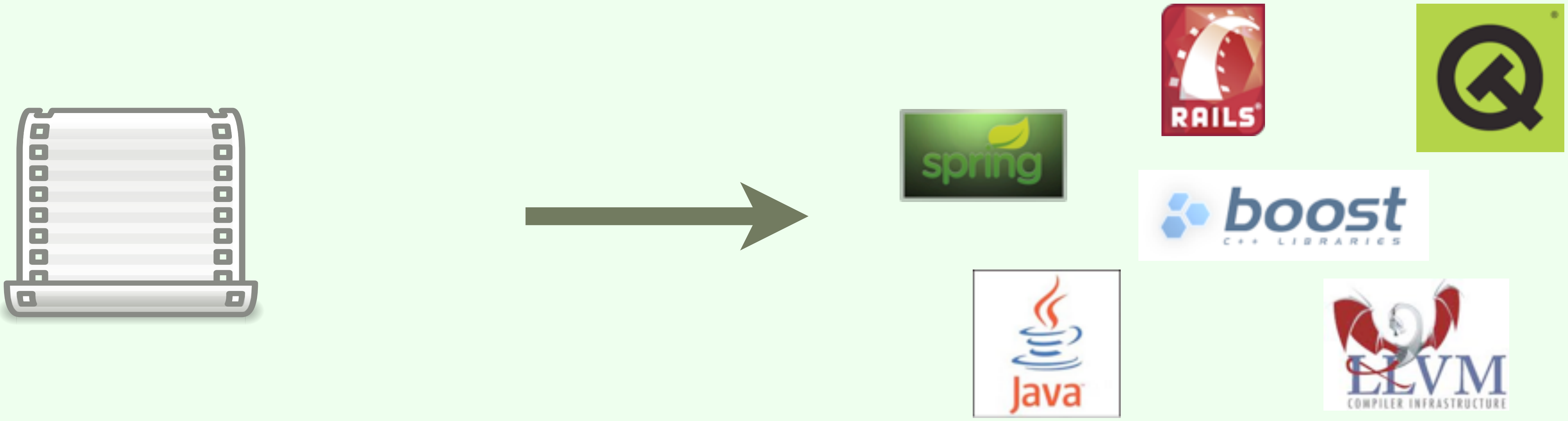
RAILS
boost
C++ LIBRARIES
Java
LLVM
COMPILER INFRASTRUCTURE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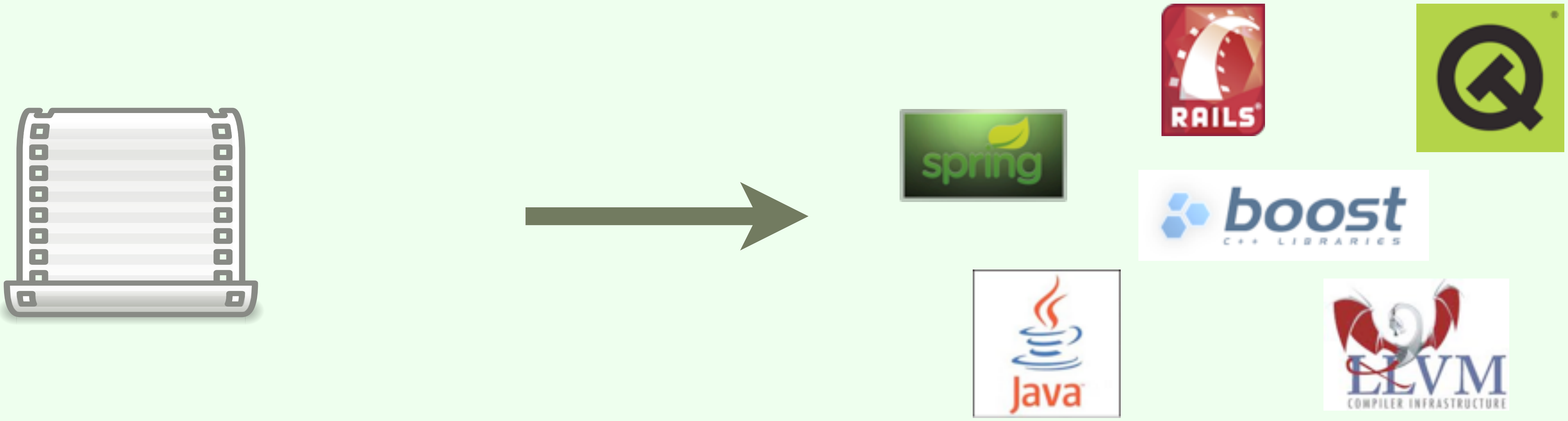
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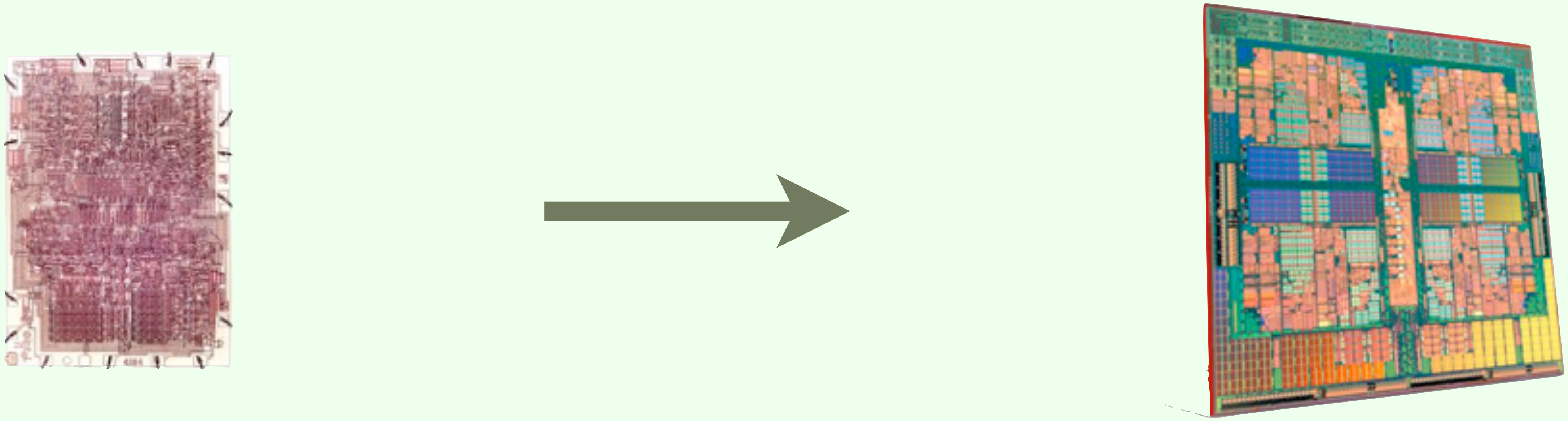
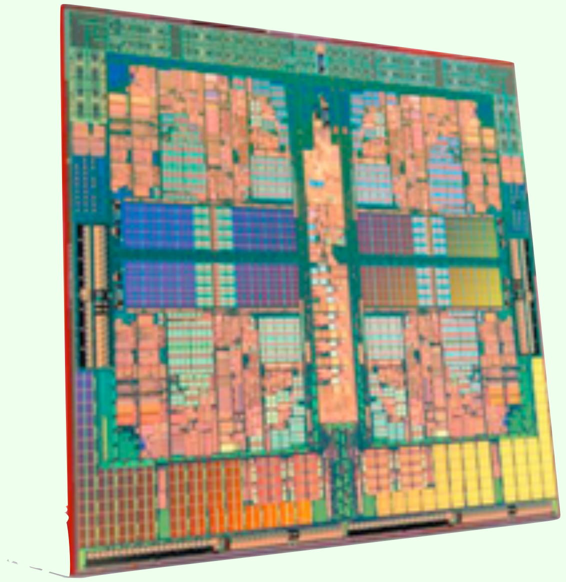


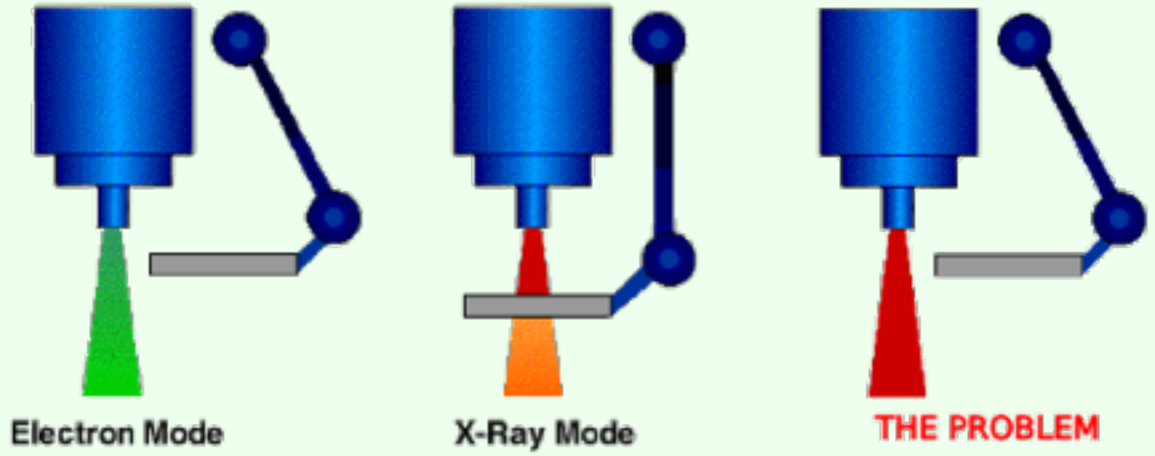
How to write and use frameworks and libraries correctly?



How to write correct parallel/concurrent code?

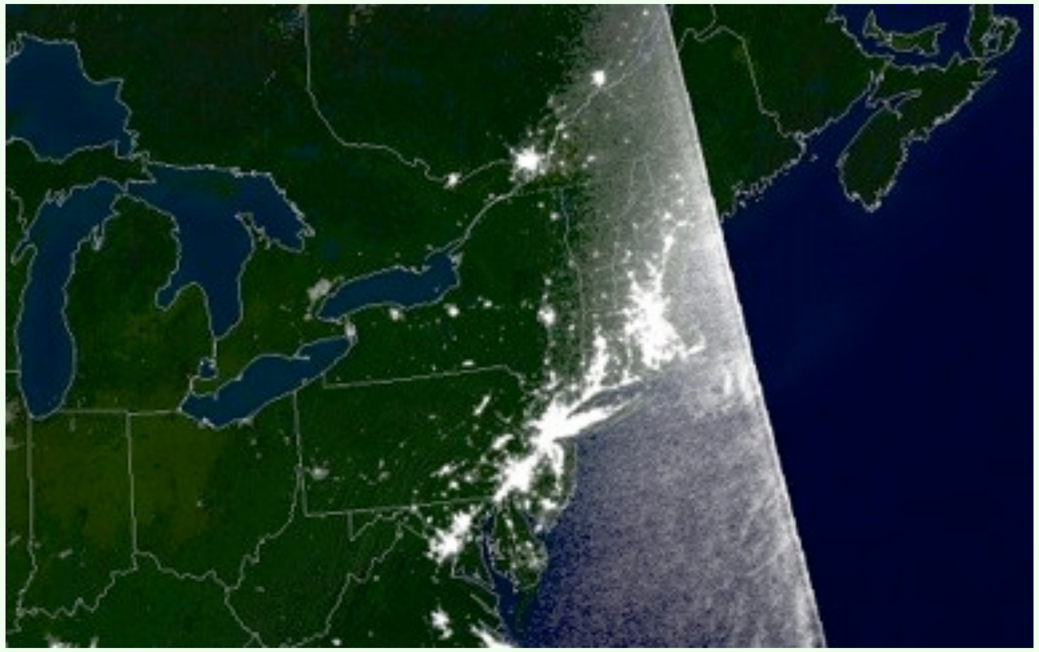
Why correctness matters?

- Therac-25
- race condition
- 3 deaths
- 3 heavy injuries



Why correctness matters?

- Blackout (2003)
- race condition
- 55,000,000 people affected



How to solve these problems?

Step by step

- Kevin Bierhoff check correct object usage:
  - **type state** to check **object protocols**
  - **access permissions** to tackle **aliasing**
- Plural [sequential protocols]

Step by step

- Nels Beckman extend Bierhoff's work to verify object protocols in concurrent settings
    - **access permission** to check correct **synchronization**
    - **access permissions** to **optimize** STM
- NIMBY/Sync' or Swim [concurrent protocols]

Step by step

- So far we can check that programs
  - obey object protocols
  - are properly synchronized
- How to write concurrent programs in first place?

How to write concurrent programs?

- Experiment
  - Implemented a few programs in various parallel programming abstractions
- Observation
  - no silver bullet
  - implicit parallelism appeared better
  - no solutions for future

Pushing the Envelope

- How should we write parallel code in 20-30 years?

Pushing the Envelope

- How should we write parallel code in 20-30 years?

> Don’t do it!
>
> -- Doug Lea

Pushing the Envelope

- make experiment
- ÆMINIUM ⟷ parallelism
  garbage collector ⟷ memory management
- automatically parallelization of code
  - composable
  - modular

Thesis Statement

The flow of access- and group-permissions provides a powerful abstraction to capture common programming idioms while simultaneous enabling the safe extraction of efficient concurrency.

In other words ...

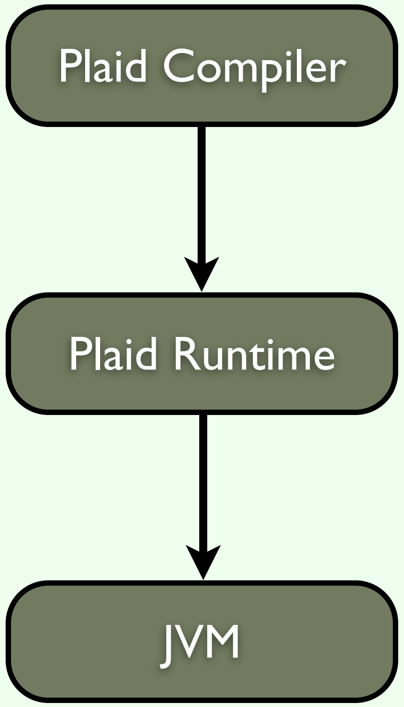
- propose abstract concept (ÆMINIUM)
- use permission information for automatic parallelization of programs
- permissions are suitable abstraction
  - can express common concurrent programming patters
  - allow us to achieve better performance

Hypotheses

- The ÆMINIUM approach is
  - **save** (i.e., no data races)
  - **efficient** (i.e., achieve speedup)
  - **practical** (i.e., express common programming paradigms)

Approach

- **formalizing** and **implementation** of the ÆMINIUM approach



Approach

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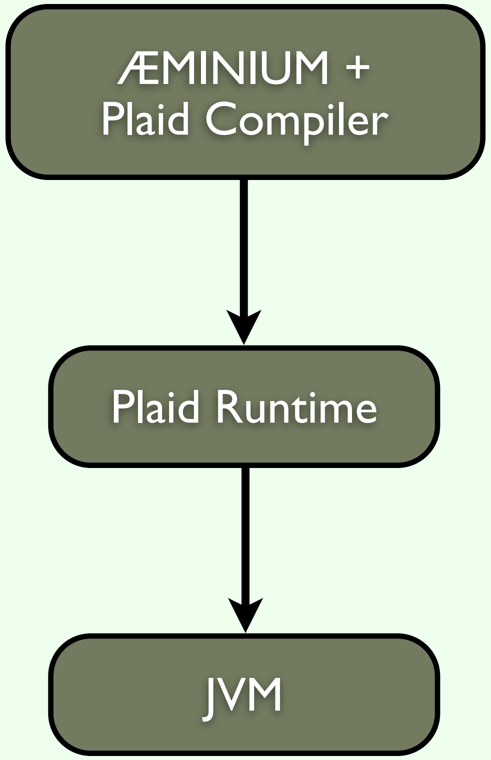
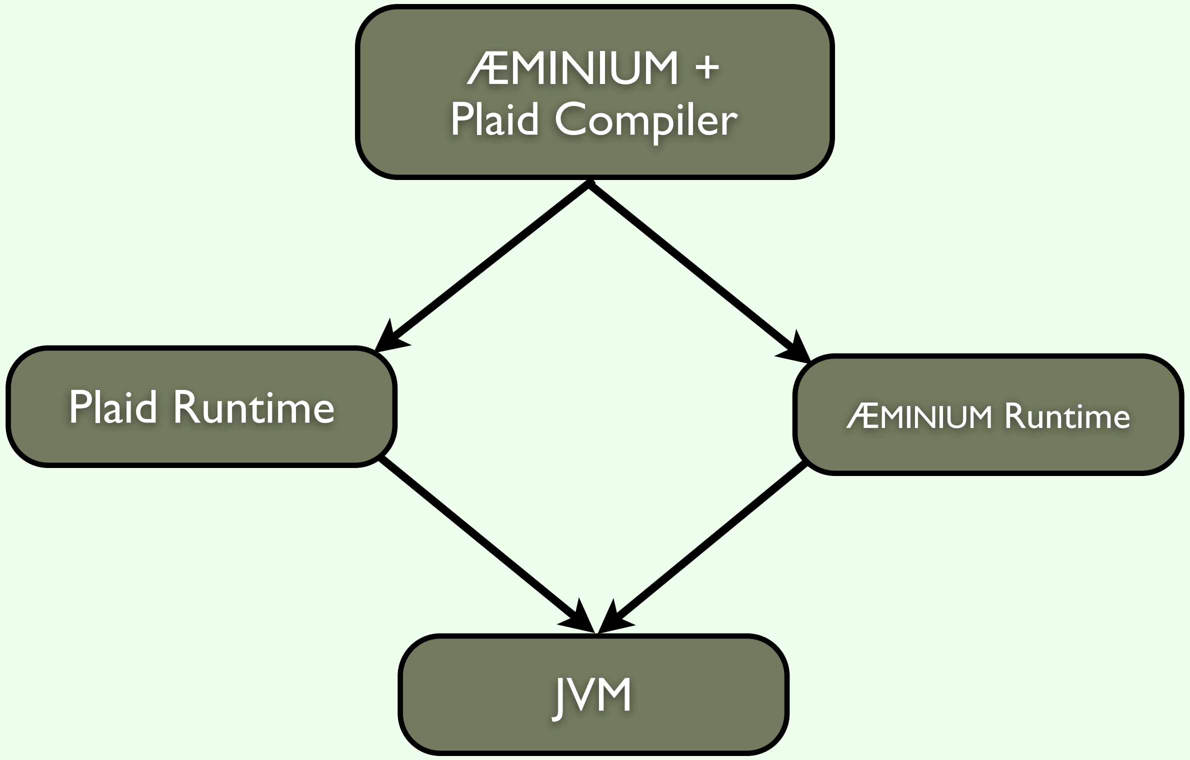


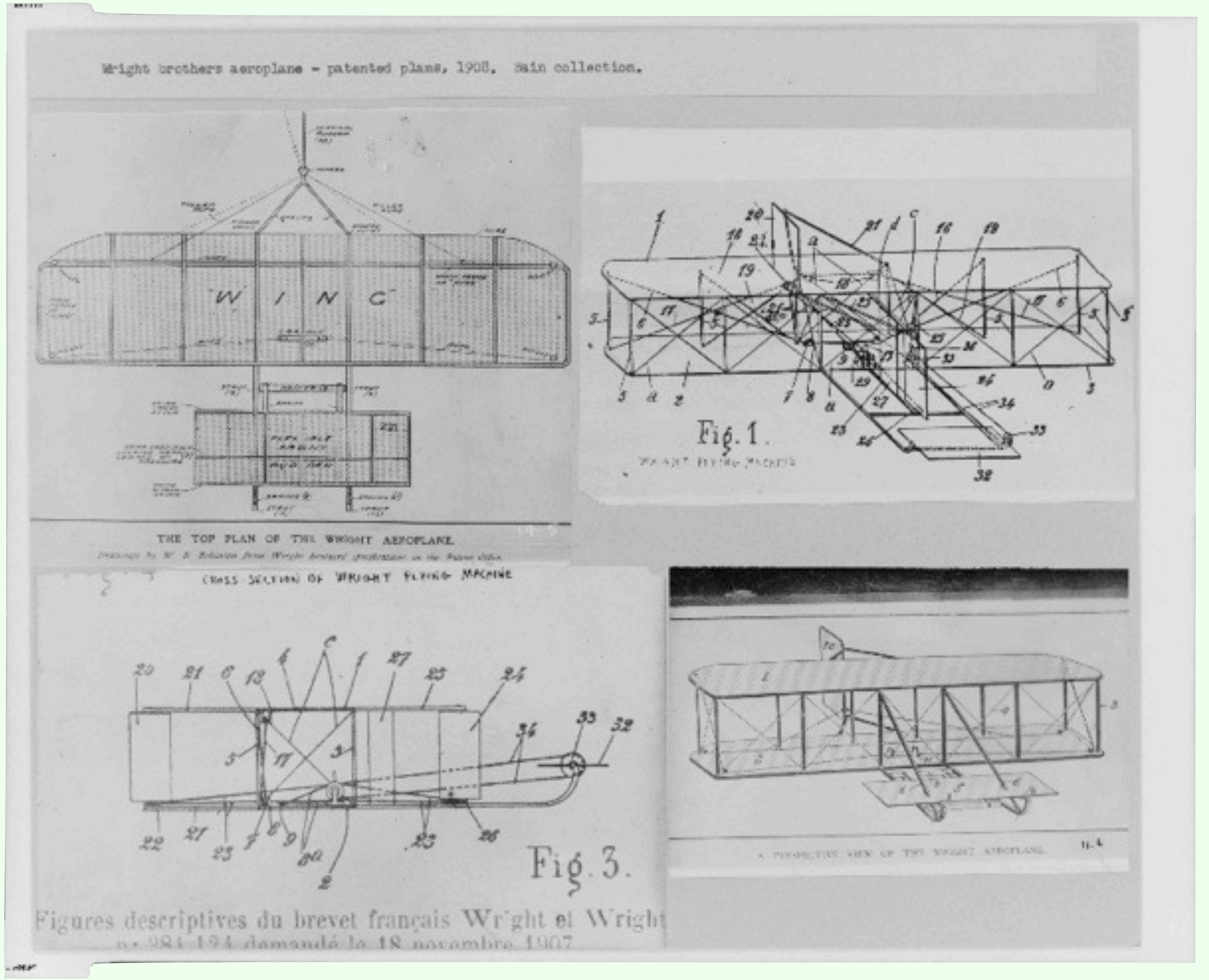
Approach

- formalizing and implementation of the ÆMINIUM approach



Contributions

- formal system of ÆMINIUM
- proof of concept implementation
- evaluation of feasibility


Wright brothers aeroplane - patented plans, 1908. Main collection.
W I N G
THE TOP PLAN OF THE WRIGHT AEROPLANE
Fig. 1.
WRIGHT FLYING MACHINE
CROSS SECTION OF WRIGHT FLYING MACHINE
Fig. 3.
Figures descriptives du brevet français Wright et Wright
n° 384 124 demandé le 18 novembre 1907
A PERSPECTIVE VIEW OF THE WRIGHT AEROPLANE

The Approach Explained

Access Permissions

- abstract capabilities associated with object references that encode
  - **access rights** (e.g., read/write)
  - **aliasing** information
- extensively used for verification (e.g. concurrency, protocols)

Access Permissions

Aliasing

Access		1	N
	RW	unique	shared
	R	immutable	immutable

Access Permissions

- **linear logic** (resource logic)

- **split** and **join**

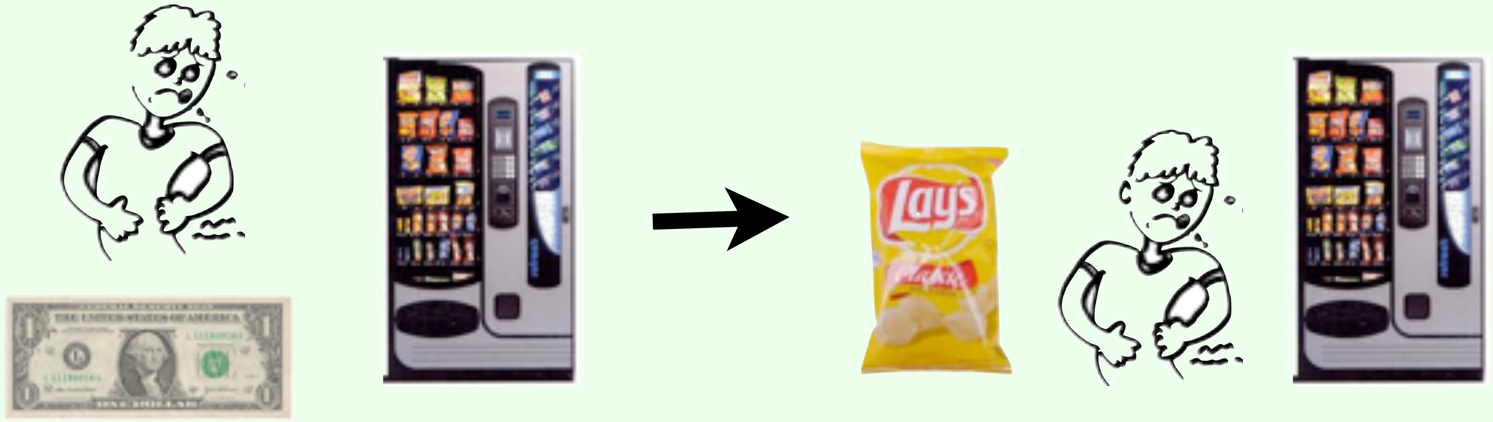
Access Permissions

- **linear logic** (resource logic)

- **split** and **join**

Access Permissions

- **linear logic** (resource logic)



- **split** and **join**

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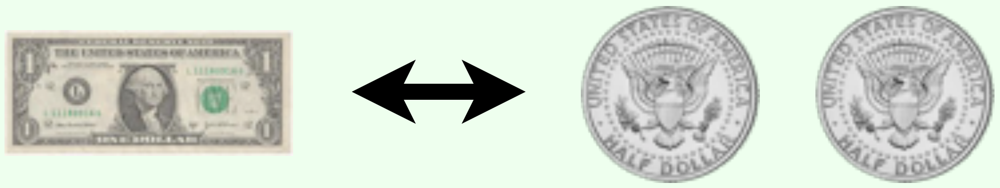

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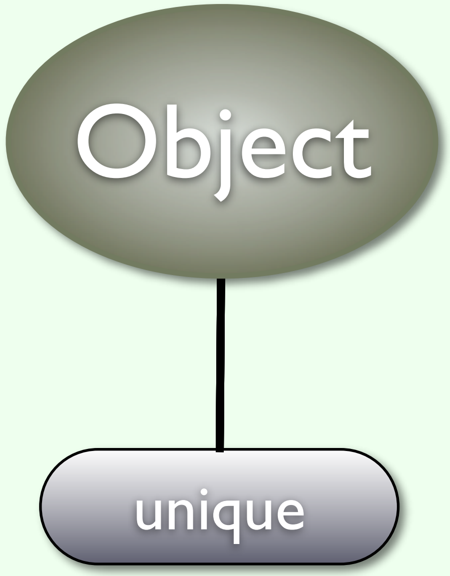
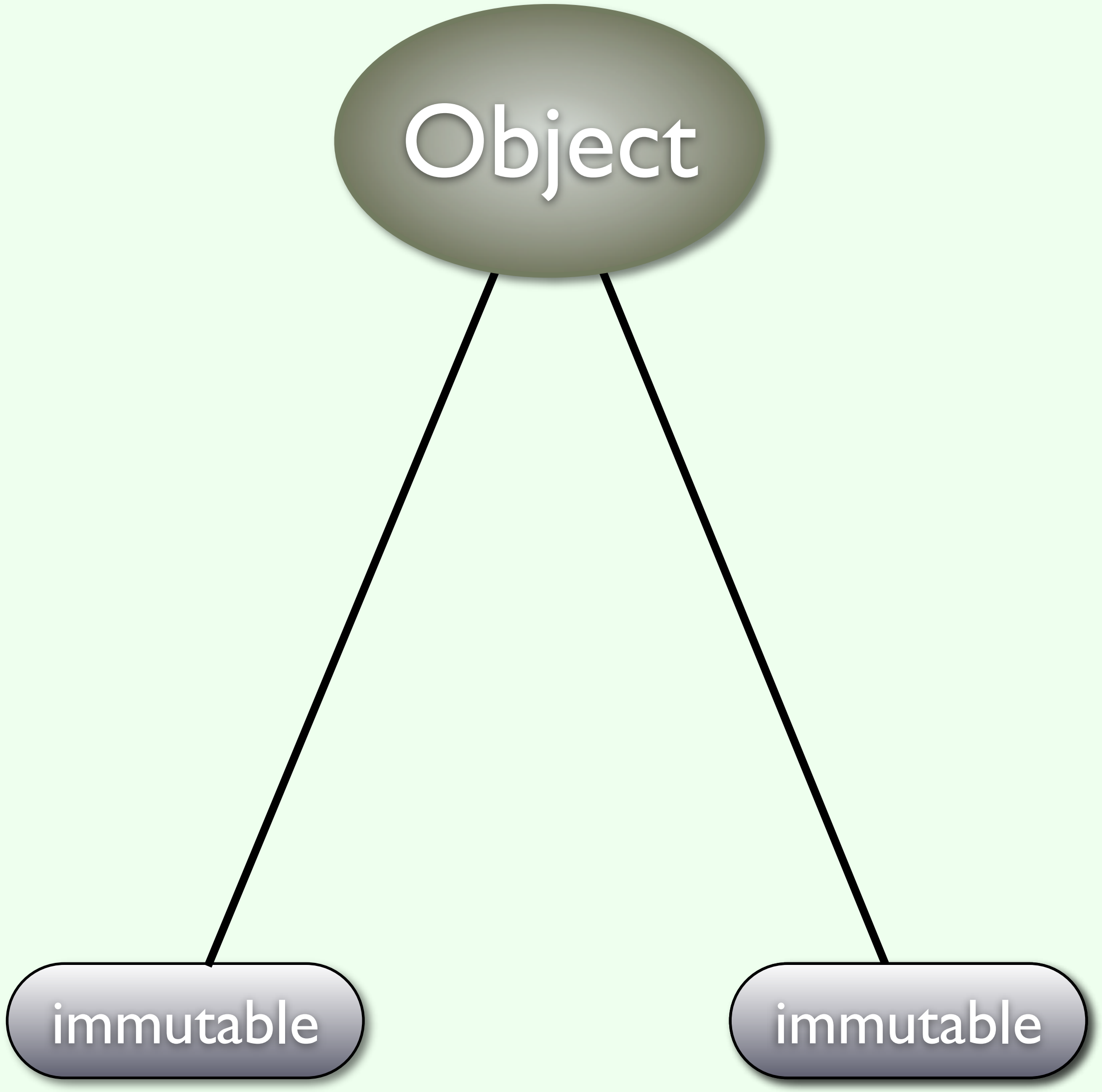


Unique Permission

- aliases = 1
- access= RW
- “thread local”
- no synchronization

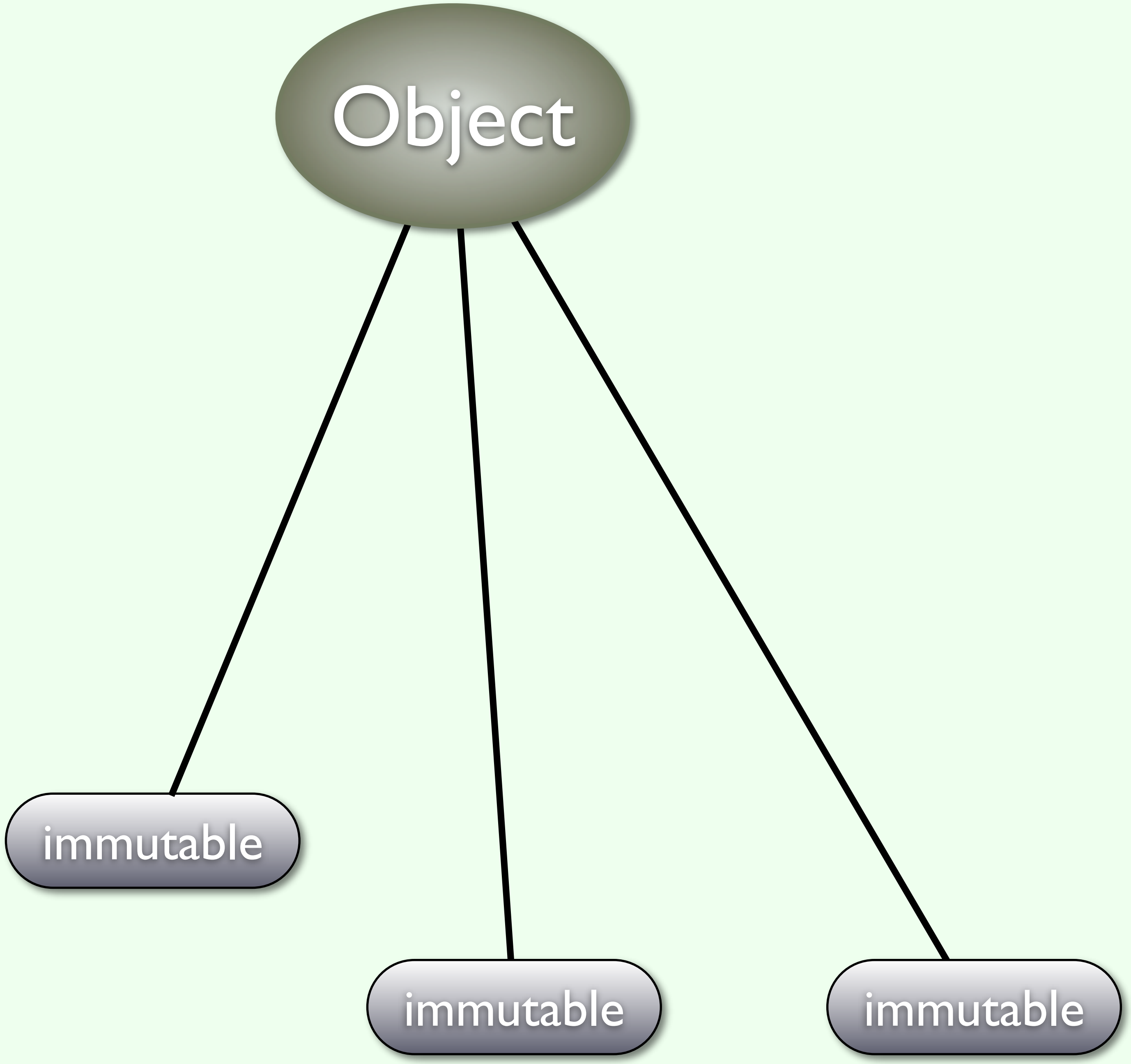
Access Permissions



Immutable Permission

- aliases = N
- access= R
- “constant”
- no synchronization

Access Permissions



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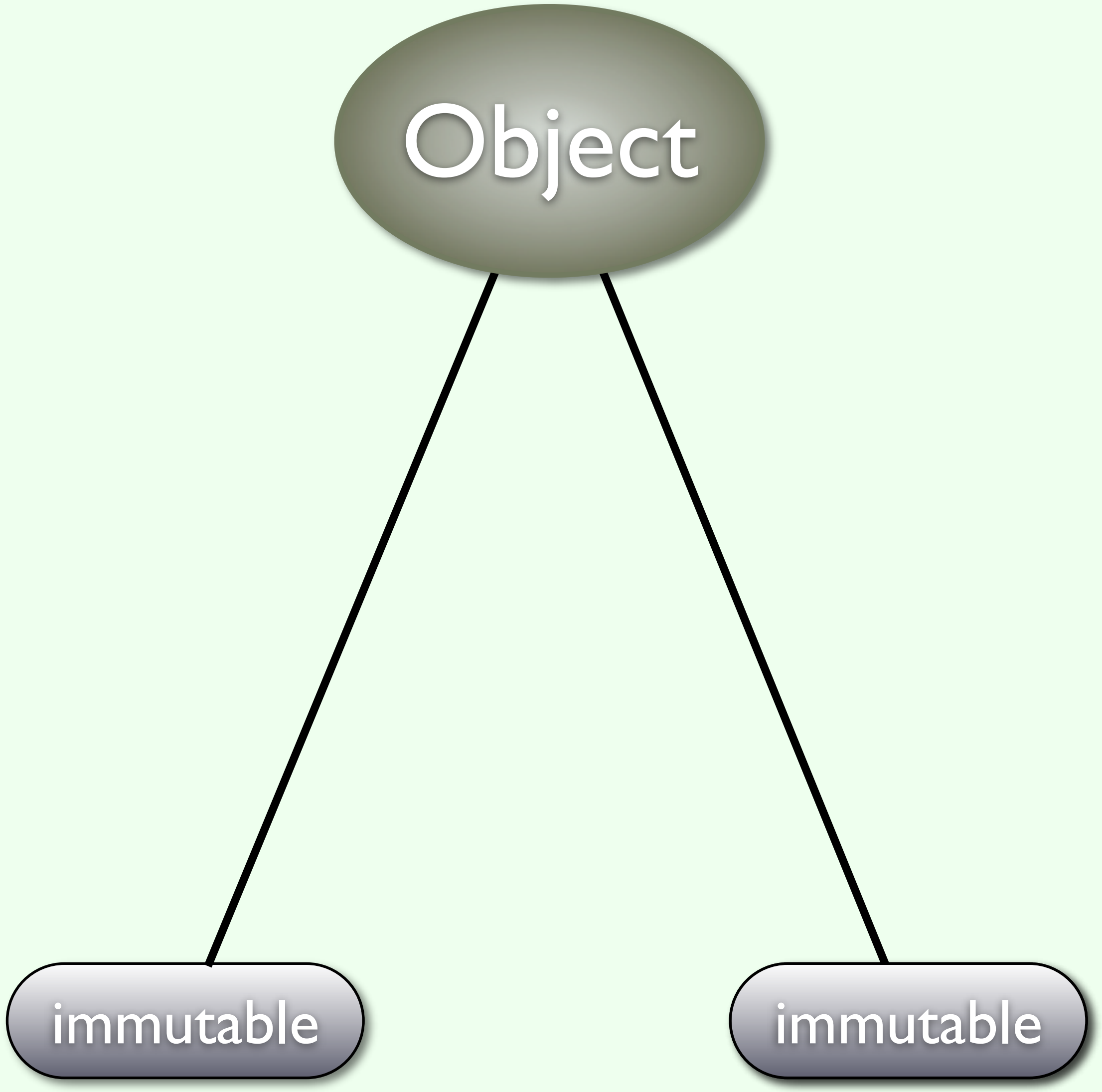

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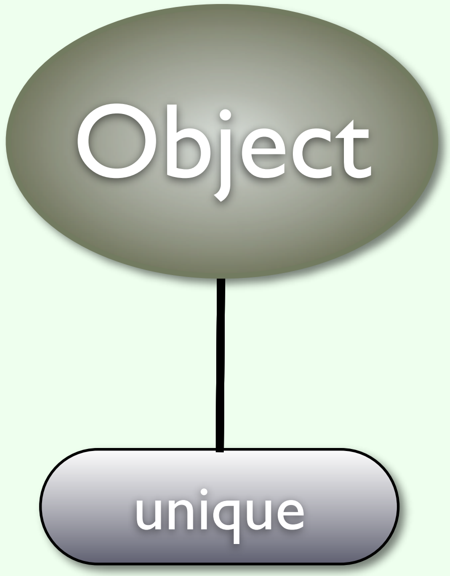

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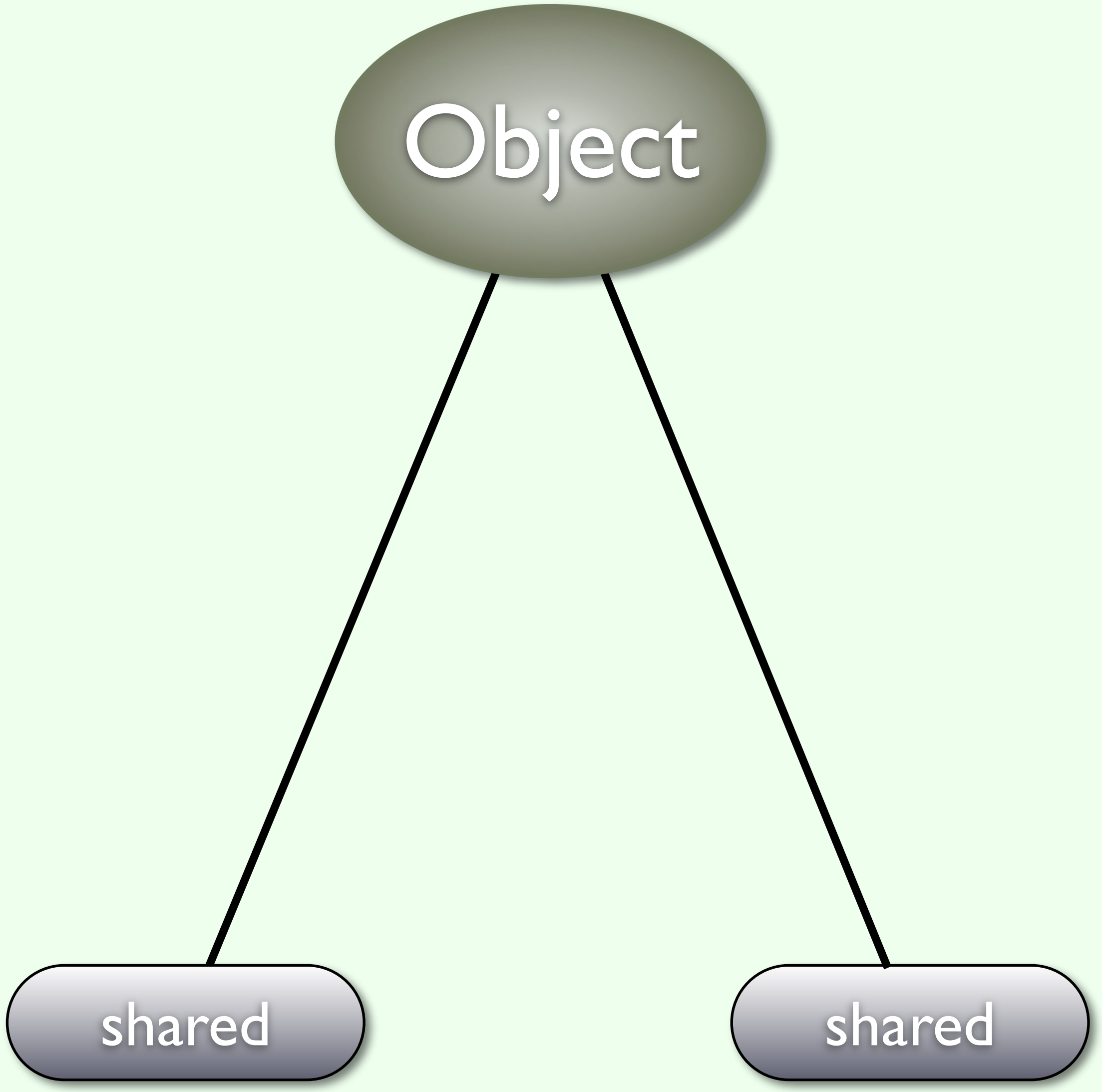
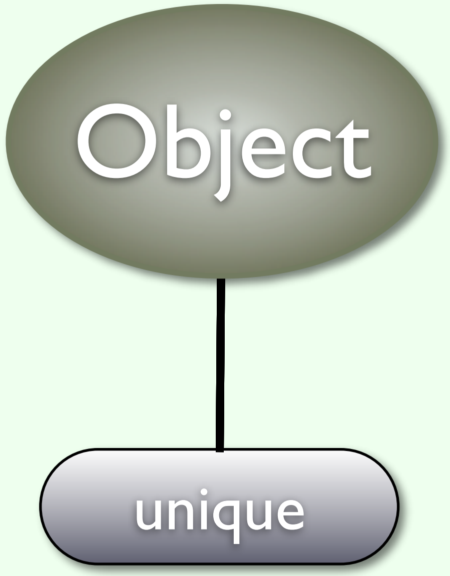
Access Permissions



Shared Permission

- aliases = N
- access= RW
- “shared data”
- requires synchronization

Access Permissions



Unique Permission

- aliases = 1
- access= RW
- “thread local”
- no synchronization

Permission Example

```
public void deposit(unique Account account, immutable Amount amount) {...}
public void withdraw(unique Account account, immutable Amount amount){...}


public void transfer(unique Account from,
                     unique Account to,
                     immutable Amount amount) {


    withdraw(from, amount);


    deposit(to, amount);


}
```

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Syntax: permission [>> permission] type var

BORROW: unique Account from

unique >> unique Account from

CHANGE: unique >> immutable Account account

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```

Using Permissions for Parallelization

- infer **permissions flow** based on **lexical order**
- define operations can run in parallel iff **intersection** of their required permissions does **not contain unique permissions**

Dataflow Example

```
transfer(unique Account from, unique Account to, immutable Amount amount)
```

Dataflow Example

transfer(unique Account from, unique Account to, immutable Amount amount)

from: unique   to: unique   amount: immutable

Dataflow Example

transfer(unique Account from, unique Account to, immutable Amount amount)

from: unique   to: unique   amount: immutable

withdraw(from, amount)

deposit(to, amount)

Dataflow Example

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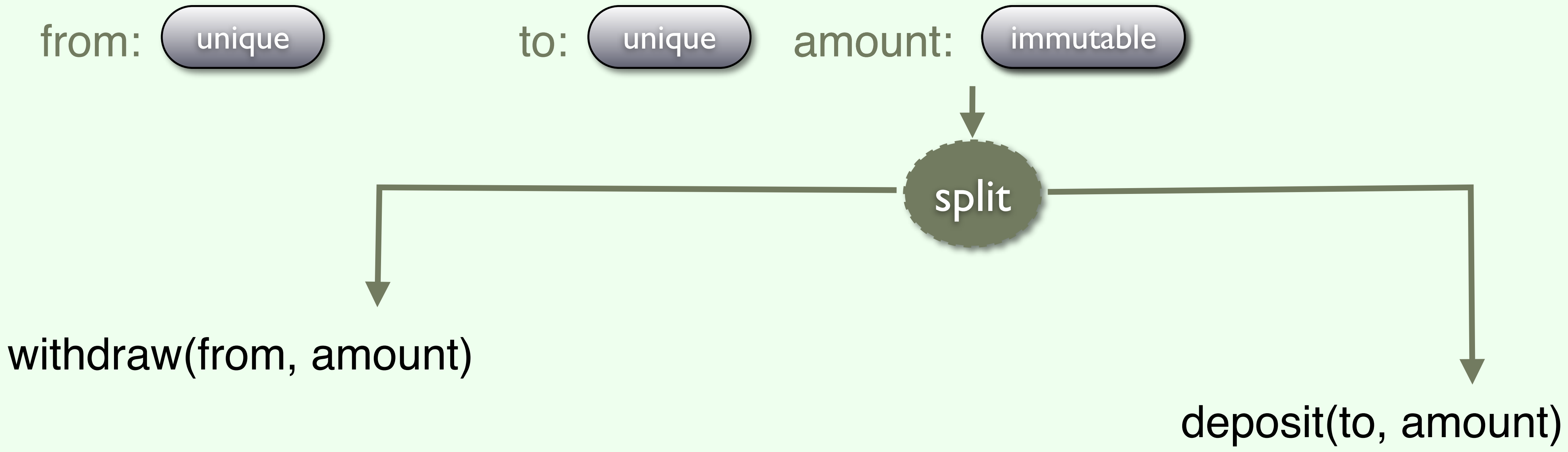


from: unique

to: unique

amount: immutable

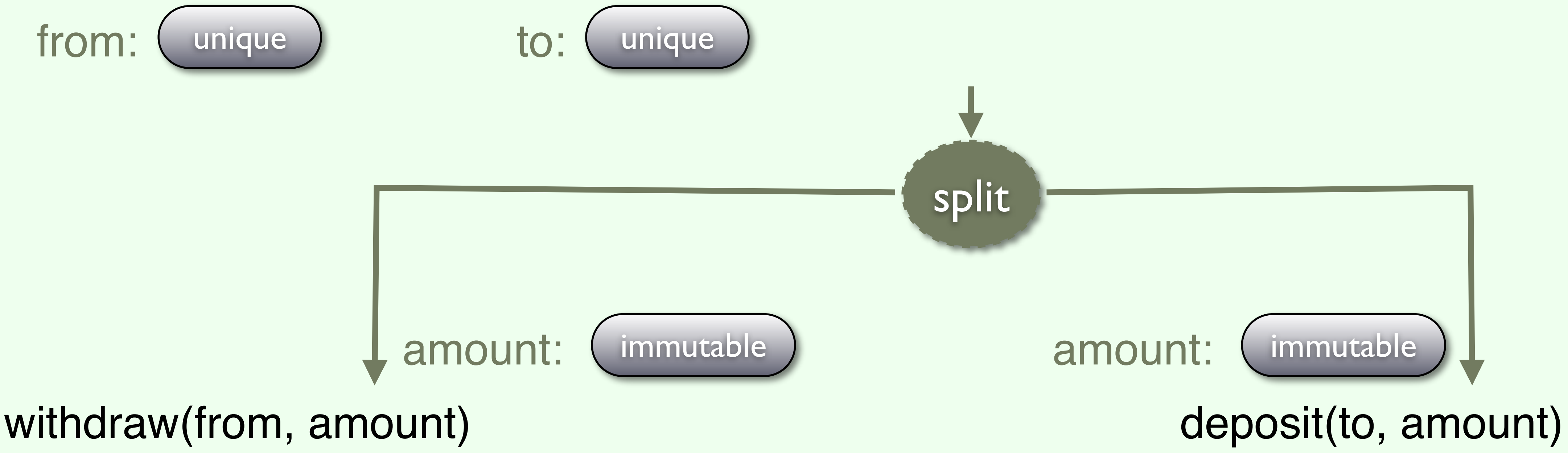
split

withdraw(from, amount)

deposit(to, amount)

Dataflow Example

transfer(unique Account from, unique Account to, immutable Amount amount)



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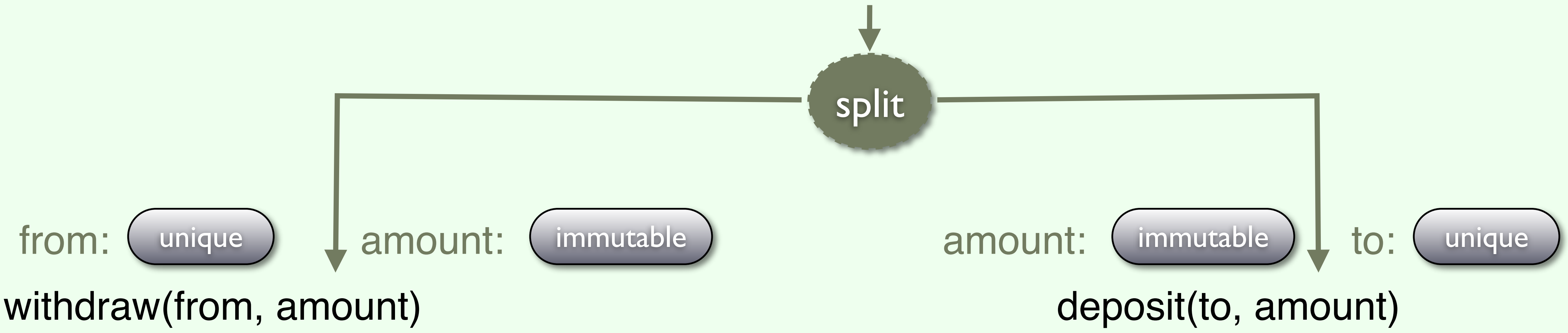

split

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amount: immutable

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amount: immutable

to: unique

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Dataflow Example

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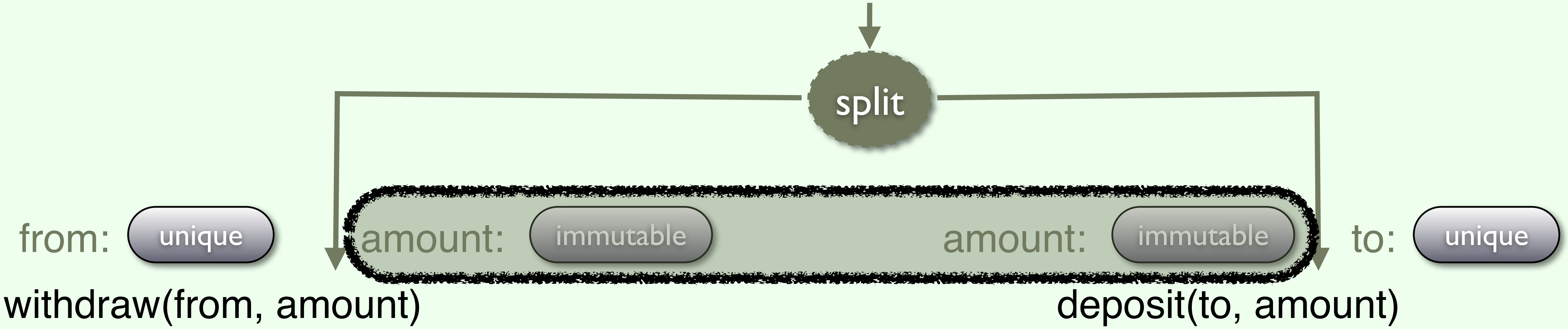

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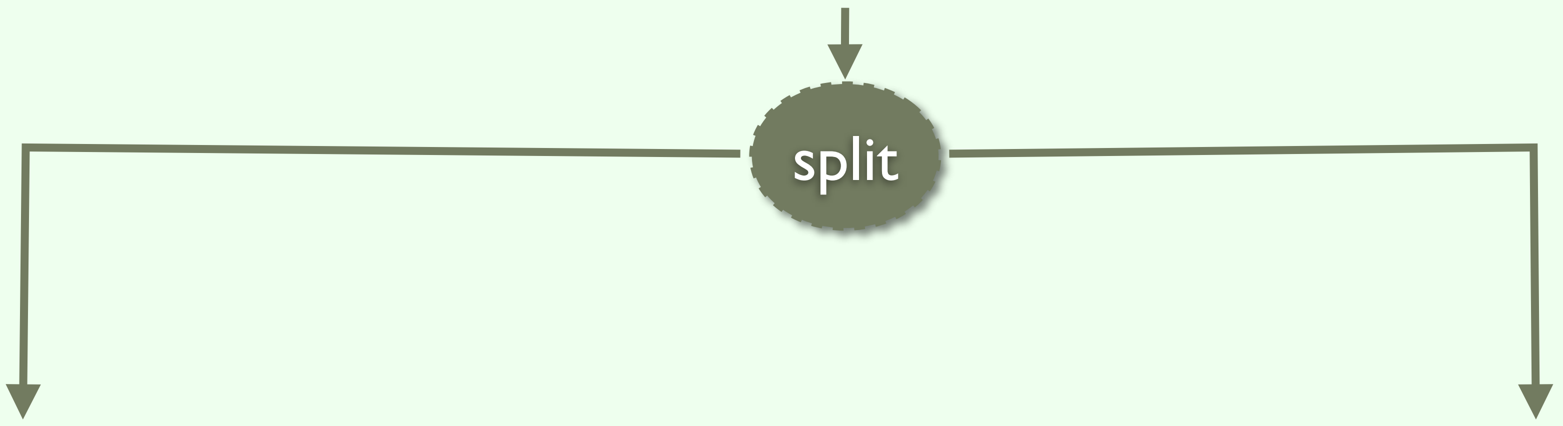

withdraw(from, amount)

from: unique amount: immutable

deposit(to, amount)

amount: immutable to: unique

Dataflow Example

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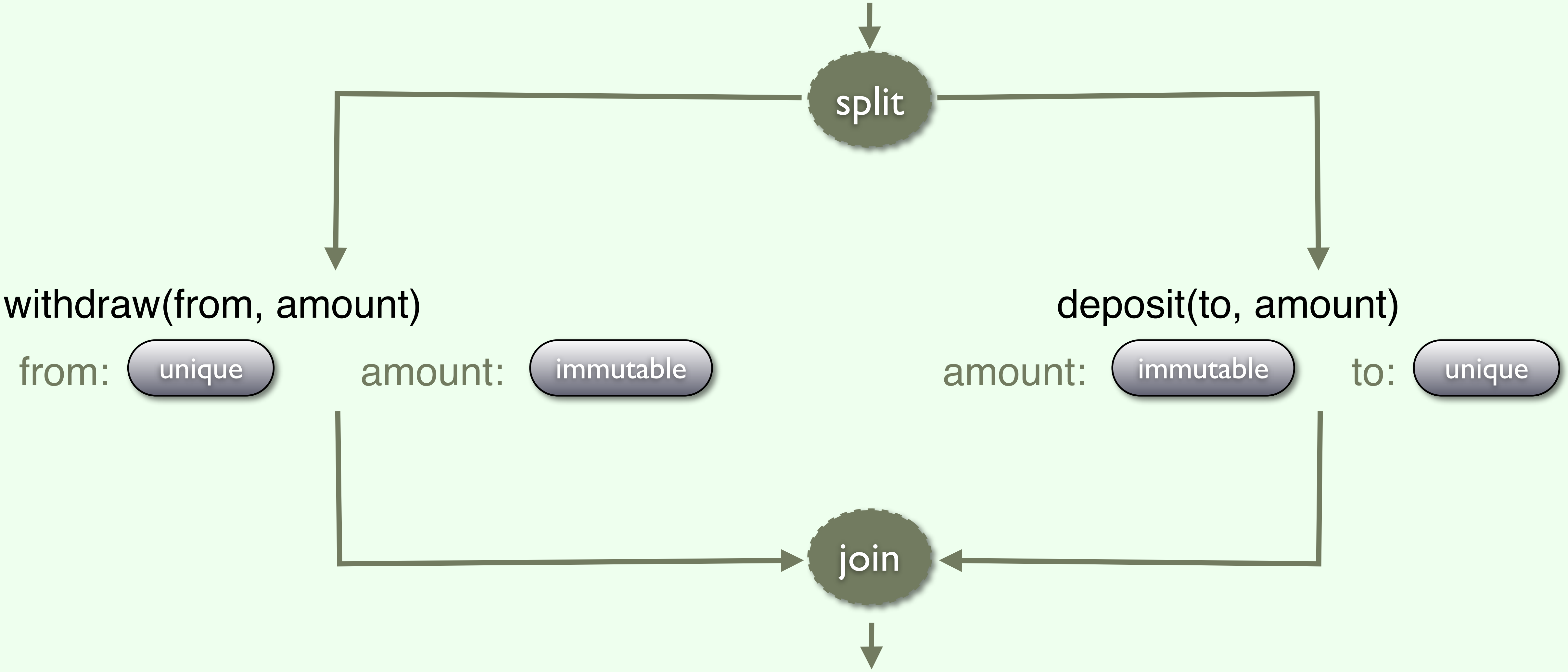


split

withdraw(from, amount)

from: unique amount: immutable

deposit(to, amount)

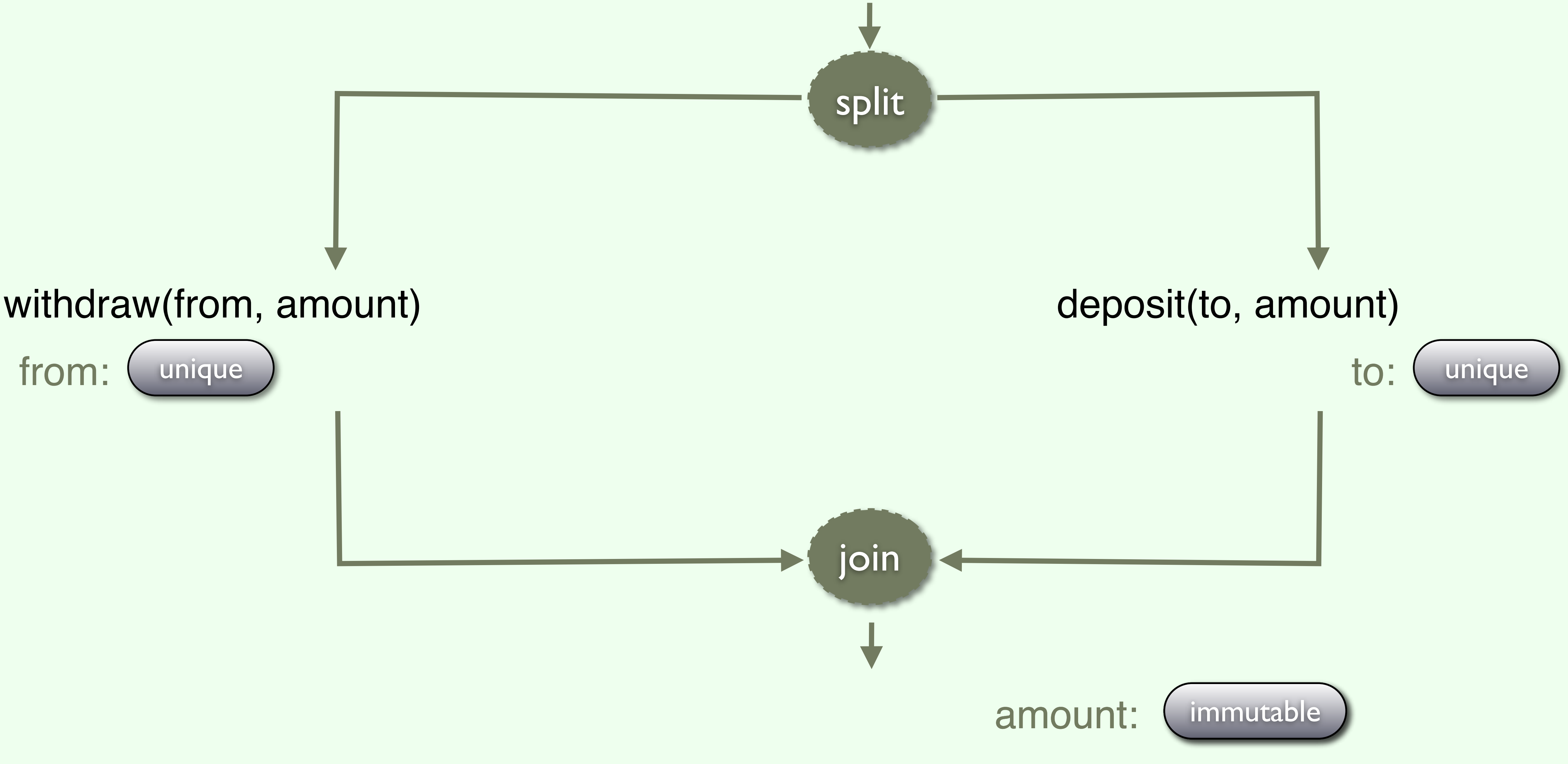
amount: immutable to: unique

join

}

Dataflow Example

transfer(unique Account from, unique Account to, immutable Amount amount)



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join

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Dataflow Example

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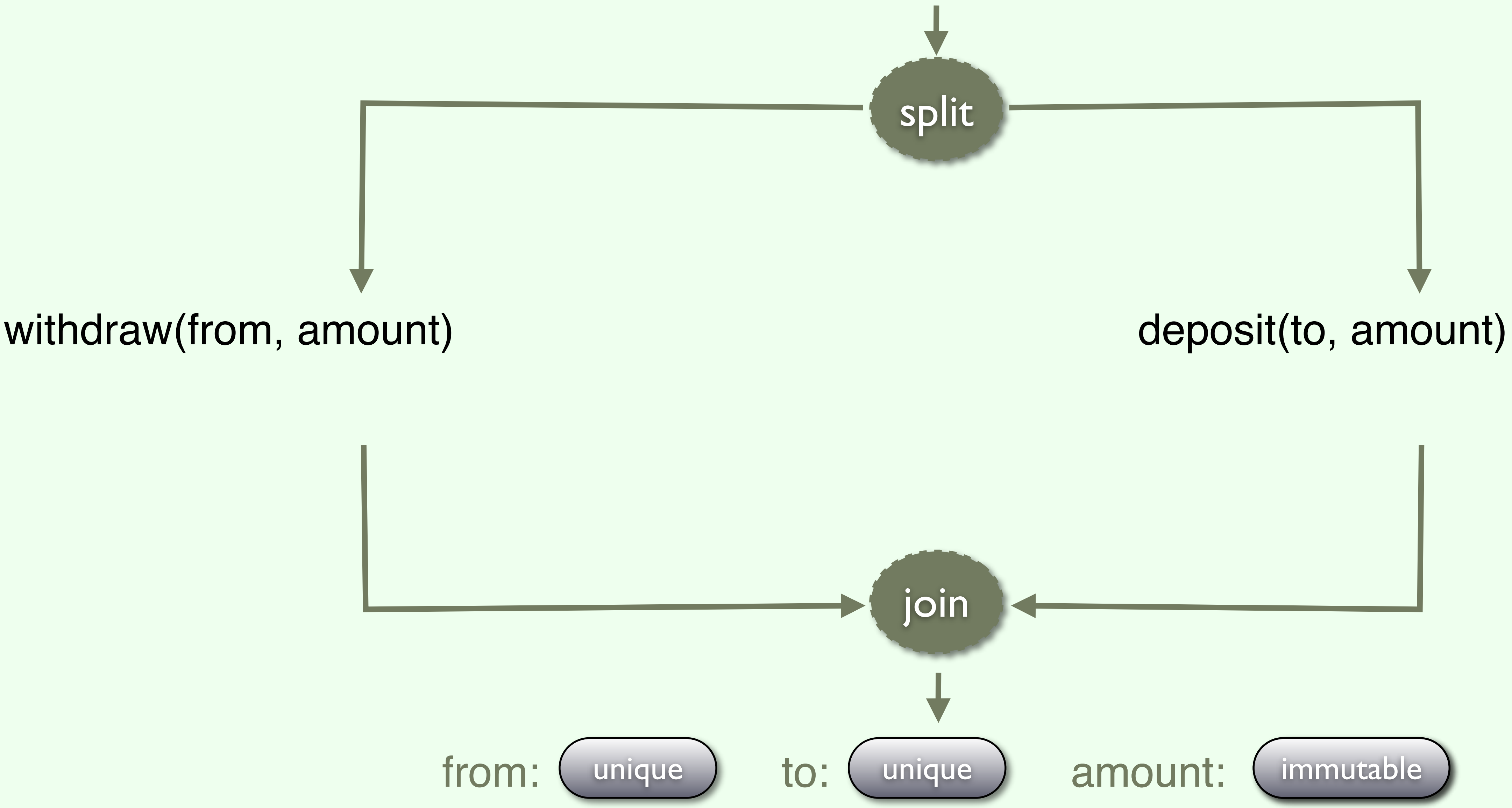

split

withdraw(from, amount)

deposit(to, amount)

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to: unique

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Dataflow Example

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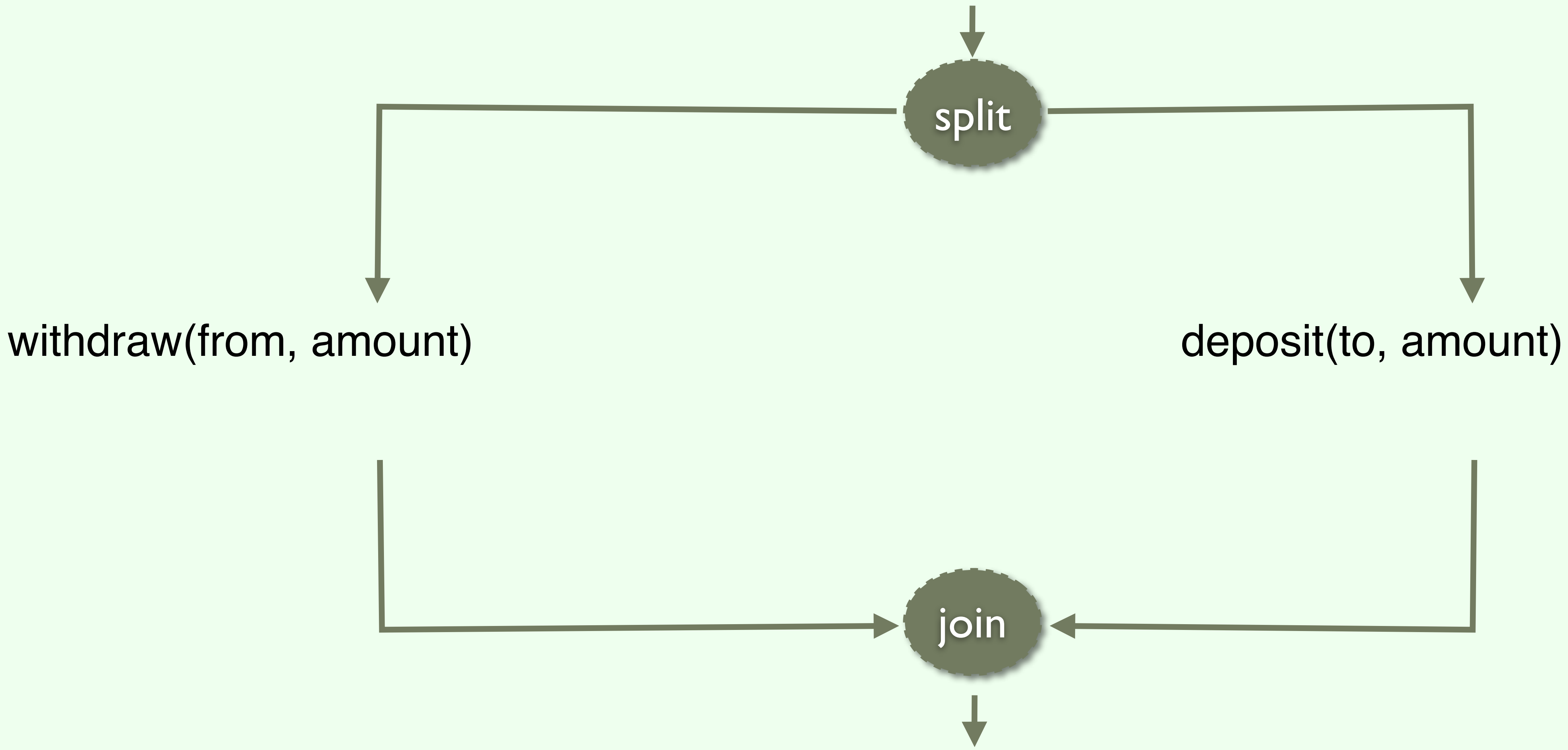

withdraw(from, amount)

deposit(to, amount)

}

Shared Data Issues

- causes **non-determinism** but sometimes order matters
  - e.g., object that needs to follow protocol
- all accesses to shared objects **require synchronization**
  - sometimes shared permissions are unavoidable
    - e.g., doubly linked list

Data Groups

- bundle shared objects into data groups
    - abstract collection of objects
    - disjoint partitions of heap

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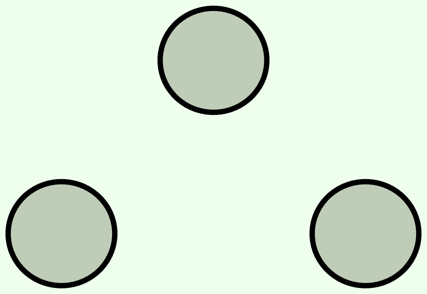

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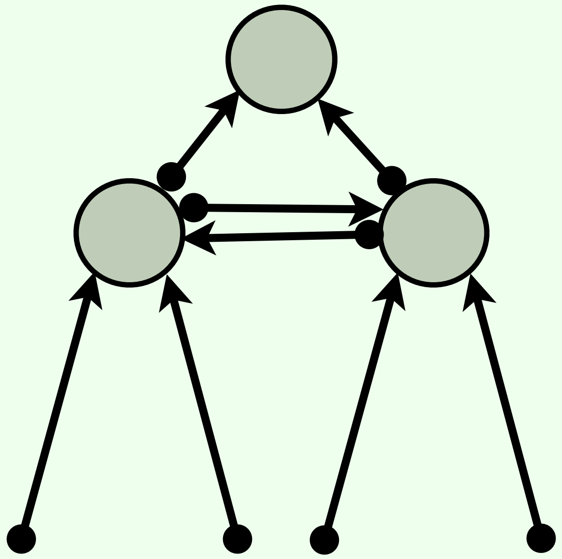

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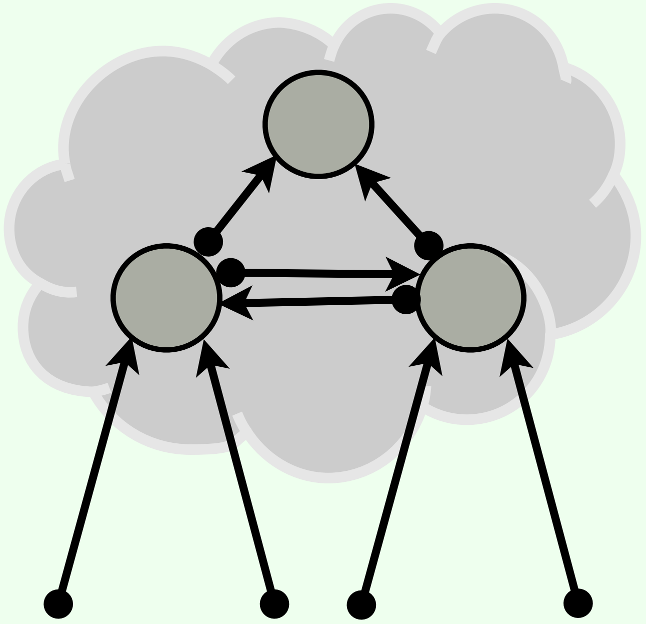
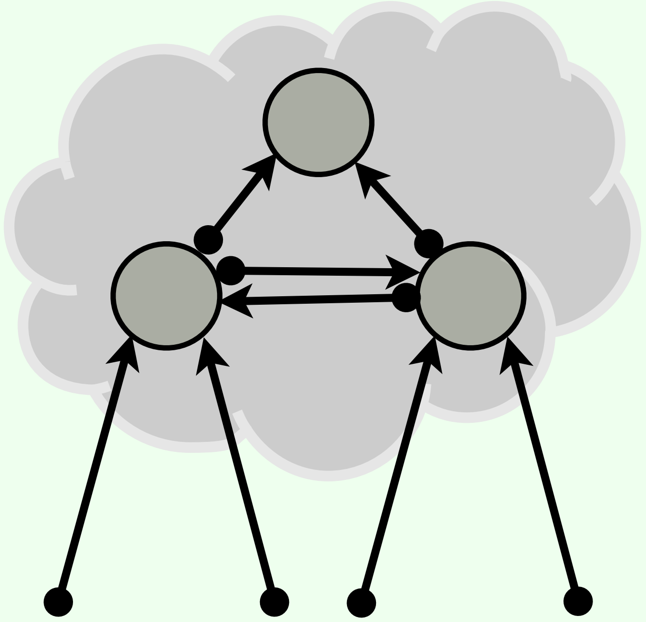


Data Groups Permissions

- similar to access permissions for data groups
- manual split/joining by user
- user controlled mechanism for granularity



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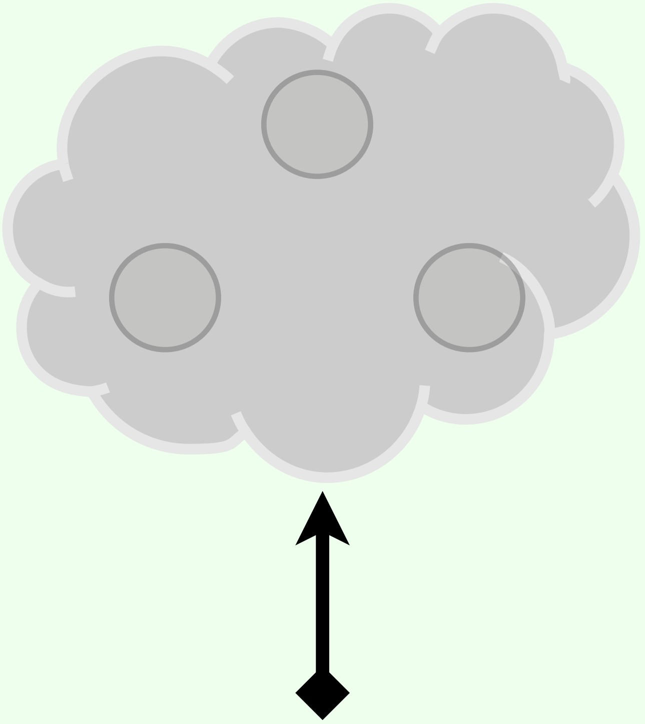
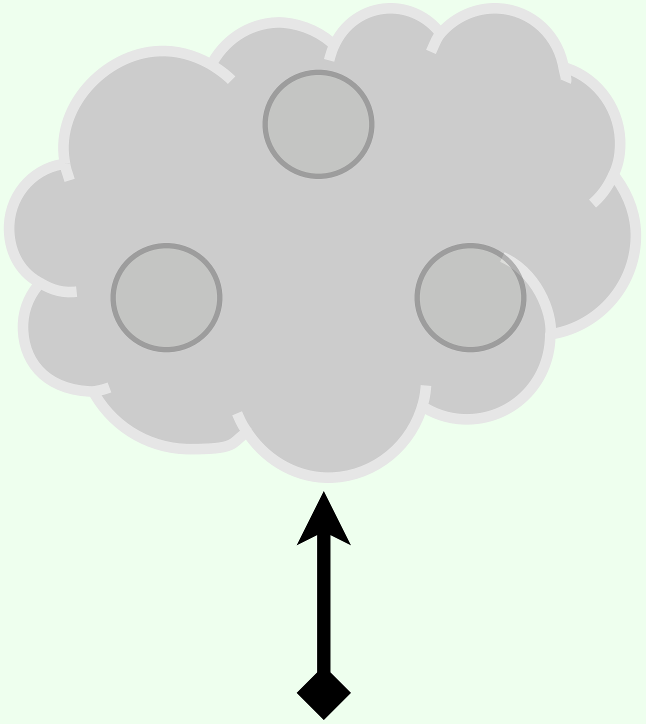
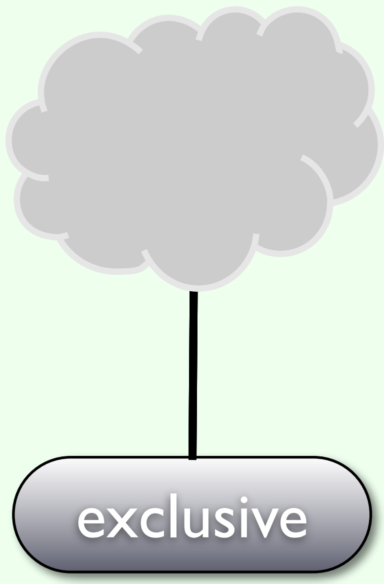


Data Groups Permissions

- data groups are embedded in objects
  - strong encapsulation, ownership
- group permissions are derived from receiver permissions



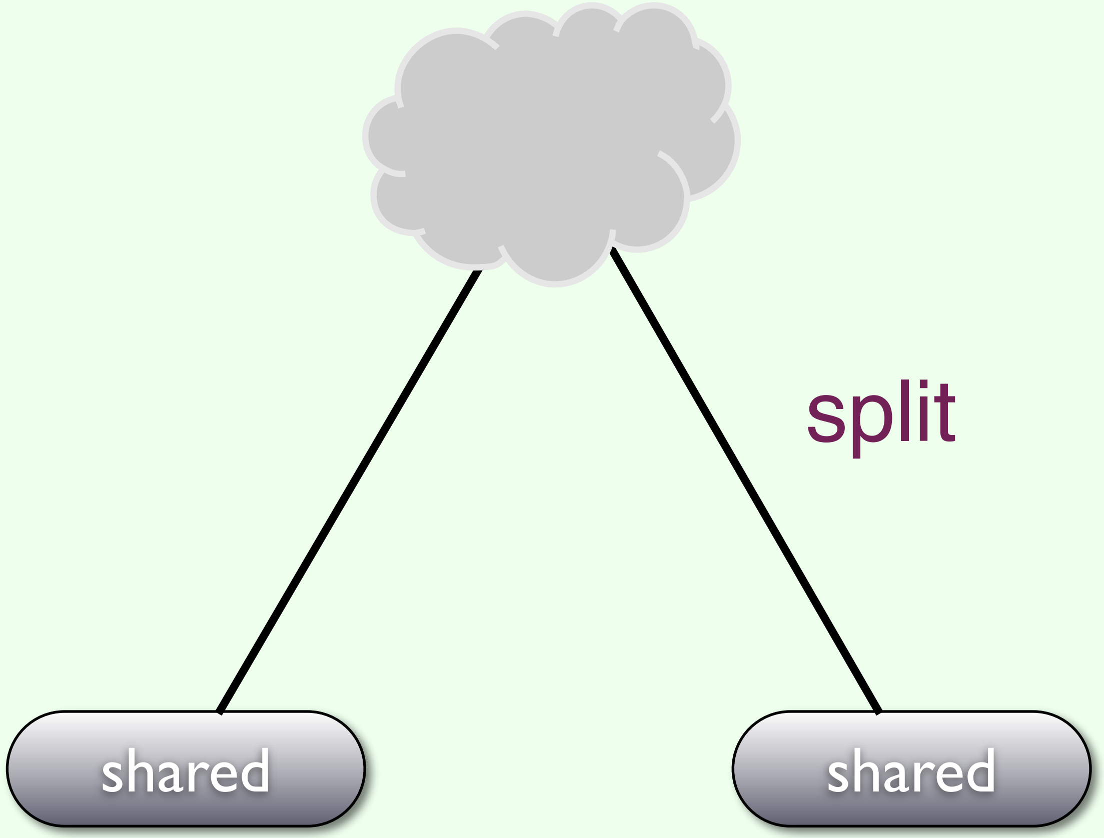
Group Permissions



Exclusive Permission

- aliases = 1
- access= RW
- “thread local”
- no synchronization

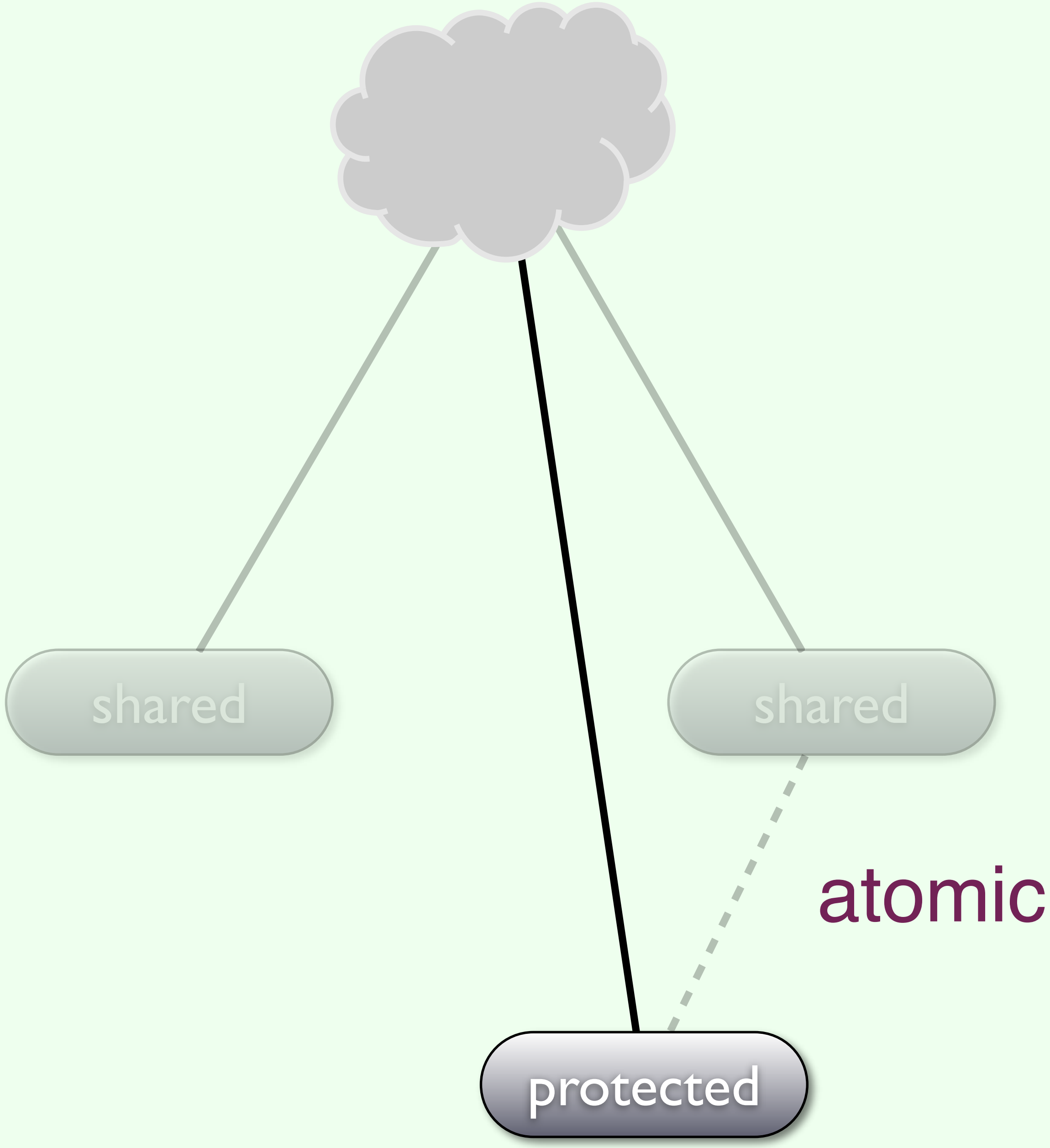
Group Permissions



Shared Permission

- aliases = N
- access= none
- “shared data”
- requires synchronization

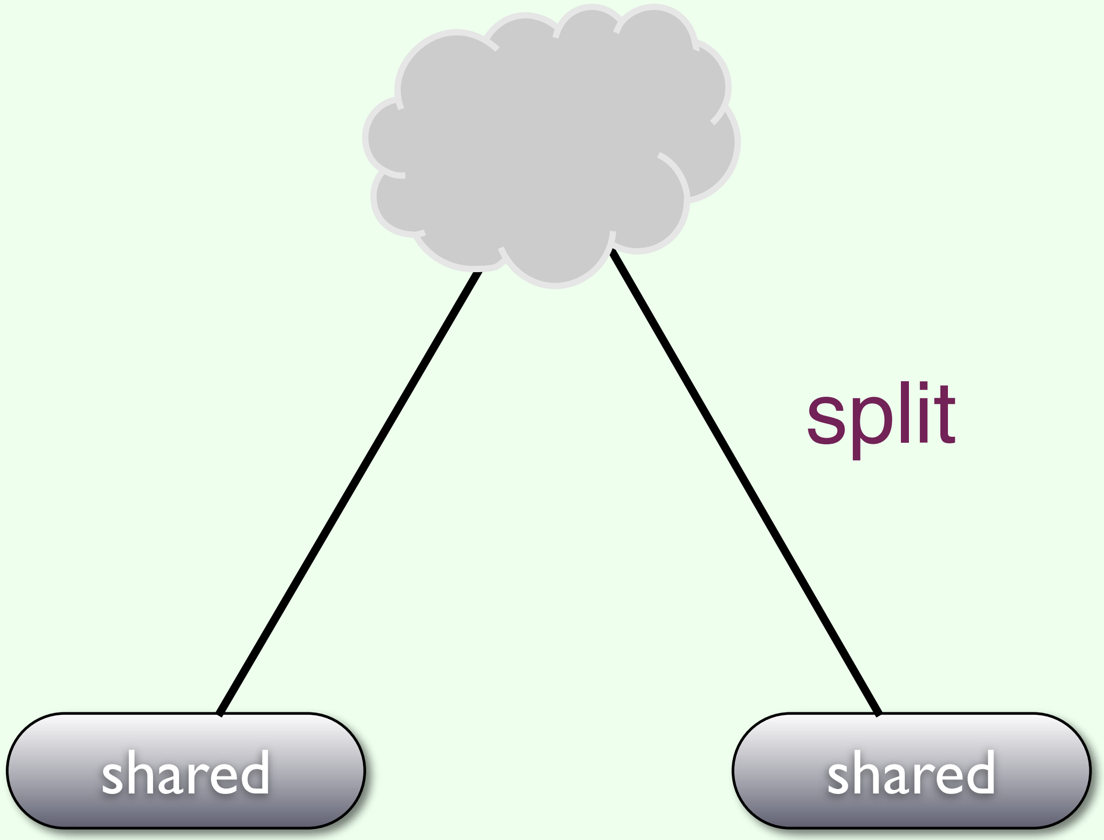
Group Permissions



atomic Permission

- aliases = 1
- access= RW
- “protected ”
- is synchronized

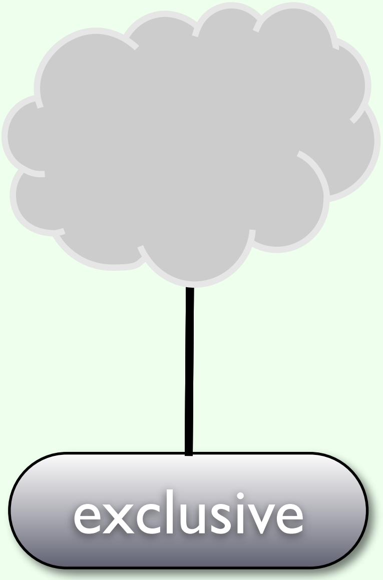
Group Permissions



Shared Permission

- aliases = N
- access= none
- “shared data”
- requires synchronization

Group Permissions



Exclusive Permission

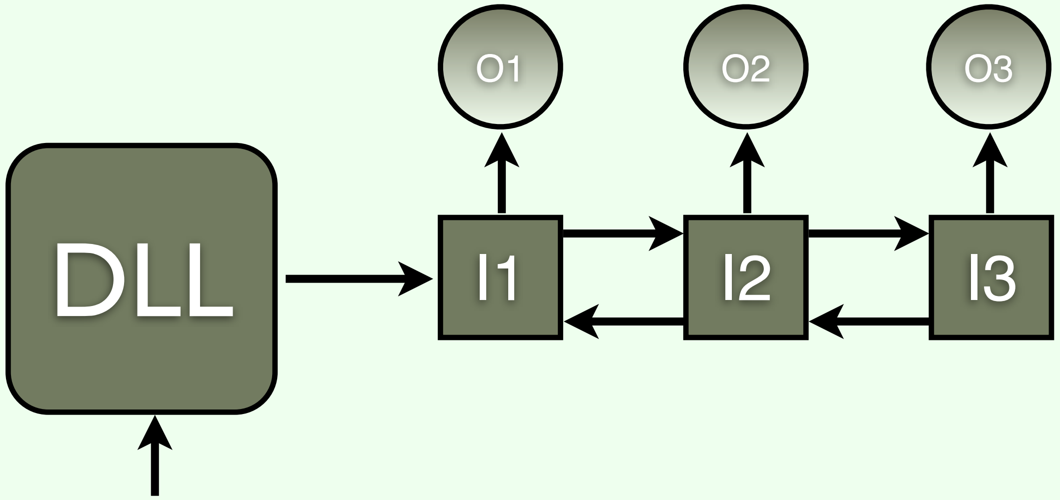
- aliases = 1
- access= RW
- “thread local”
- no synchronization

Data Group Example

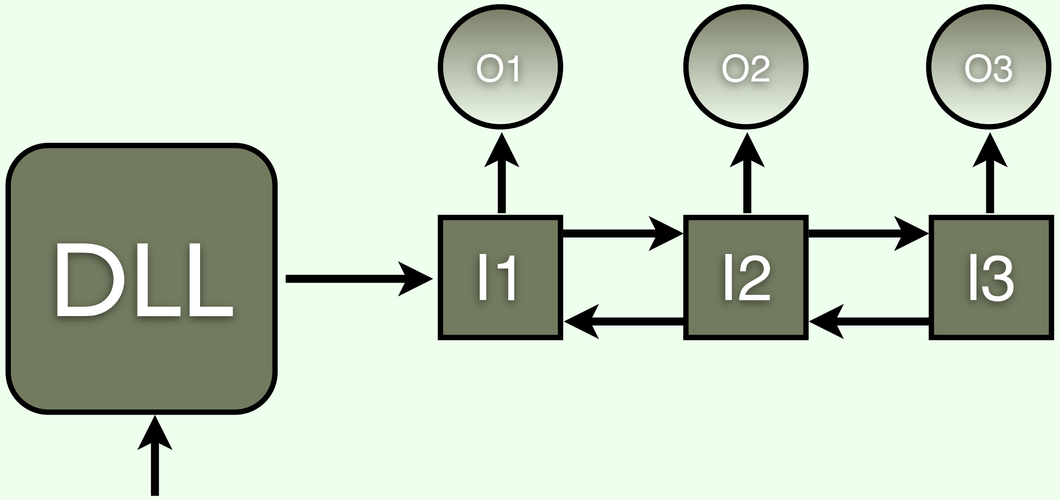
```
class DLLItem {
    public Object data;
    public DLLItem prev;
    public DLLItem next;
}

public class DLL {
    private DLLItem head;

    public void add(Object data) {
         DLLItem li = new DLLItem();
         this.head.prev = li;
         li.next = this.head;
         li.data = data;
         this.head = li;
    }
}
```



Data Group Example



```
class DLLItem {
    public        Object data;
    public        DLLItem prev;
    public        DLLItem next;
}

public class DLL {
    private        DLLItem head;

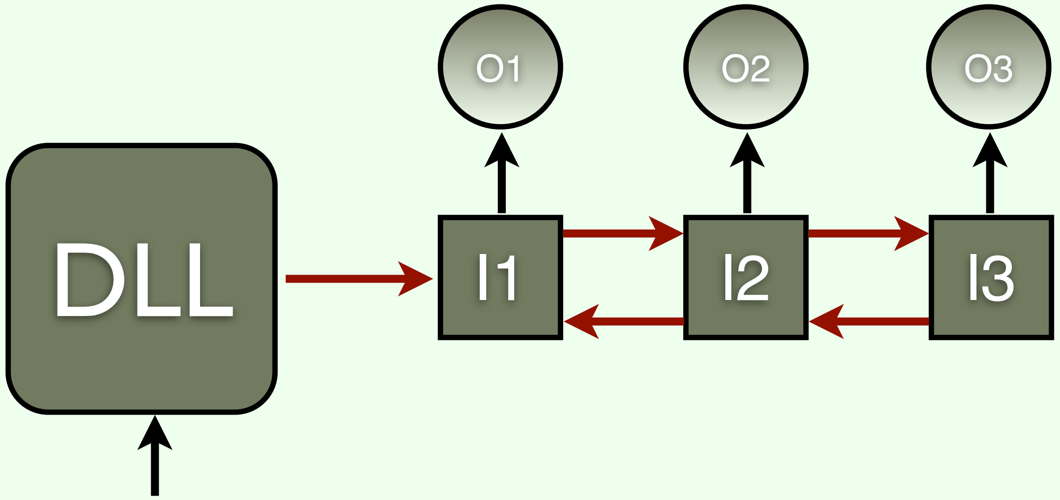
    public void add(               Object data)          {
                DLLItem li = new DLLItem();
         this.head.prev = li;
         li.next = this.head;
         li.data = data;
         this.head = li;
    }
}
```

Data Group Example

```
class DLLItem {
    public        Object data;
    public shared DLLItem prev;
    public shared DLLItem next;
}

public class DLL {
    private shared DLLItem head;

    public void add(              Object data)          {
        shared DLLItem li = new DLLItem();
        this.head.prev = li;
        li.next = this.head;
        li.data = data;
        this.head = li;
    }
}
```

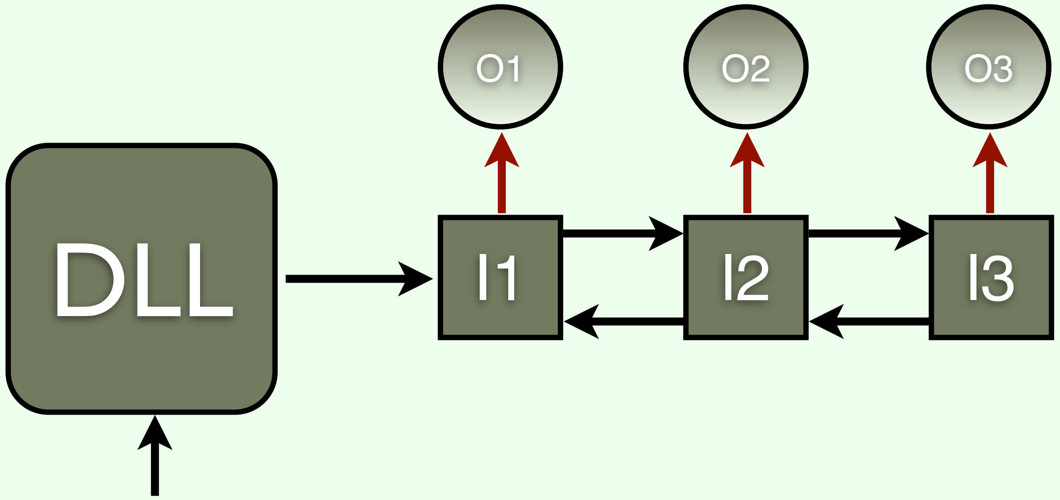


Data Group Example

```
class DLLItem {
    public unique Object data;
    public shared DLLItem prev;
    public shared DLLItem next;
}

public class DLL {
    private shared DLLItem head;

    public void add(unique >> none Object data)          {
         shared DLLItem li = new DLLItem();
         this.head.prev = li;
         li.next = this.head;
         li.data = data;
         this.head = li;
    }
}
```

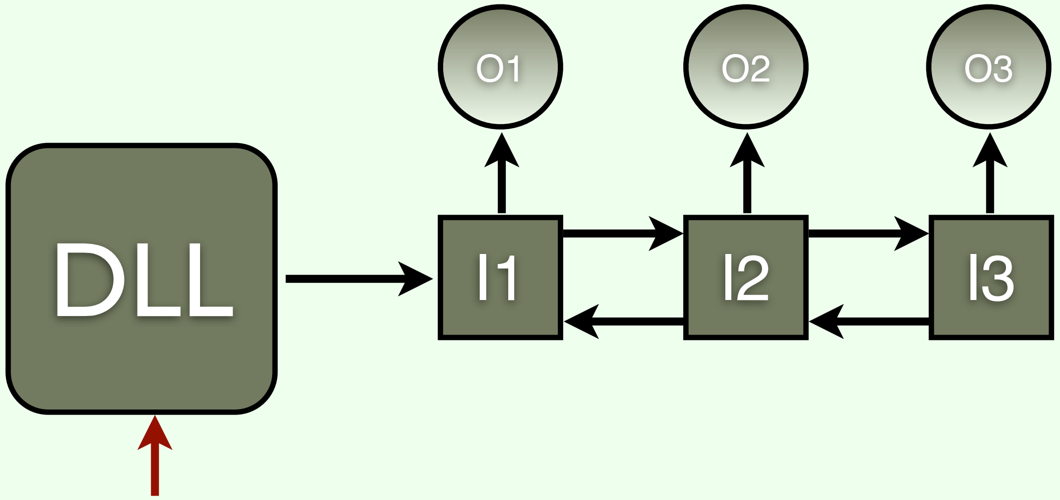


Data Group Example

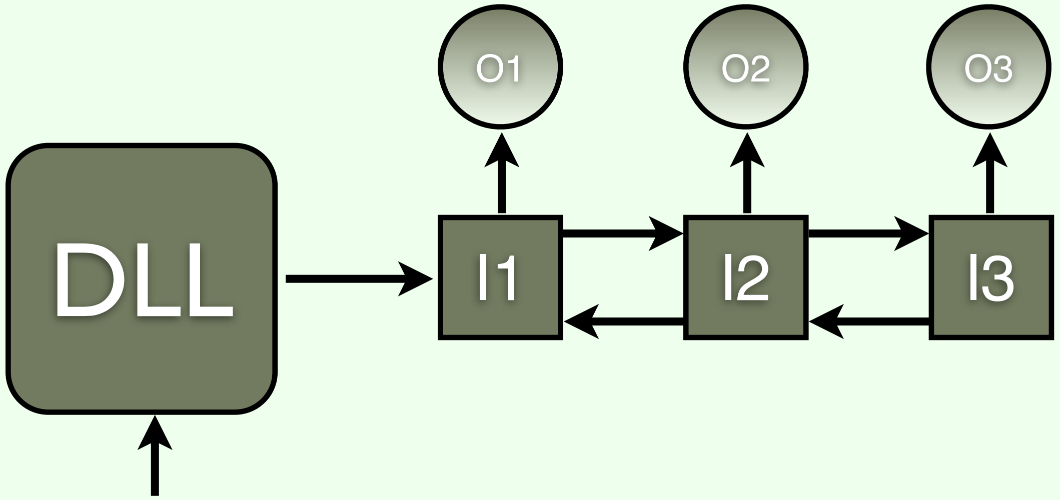
```
class DLLItem {
    public unique Object data;
    public shared DLLItem prev;
    public shared DLLItem next;
}

public class DLL {
    private shared DLLItem head;

    public void add(unique >> none Object data) : unique {
        shared DLLItem li = new DLLItem();
        this.head.prev = li;
        li.next = this.head;
        li.data = data;
        this.head = li;
    }
}
```



Data Group Example



```
class DLLItem {
    public unique Object data;
    public shared DLLItem prev;
    public shared DLLItem next;
}

public class DLL {
    private shared DLLItem head;

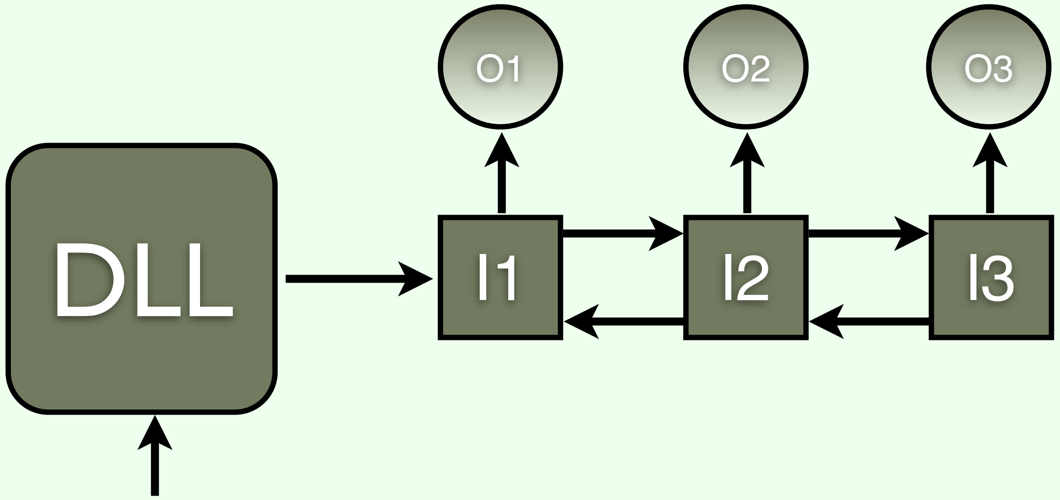
    public void add(unique >> none Object data) : unique {
         shared DLLItem li = new DLLItem();
         this.head.prev = li;
         li.next = this.head;
         li.data = data;
         this.head = li;
    }
}
```

Data Group Example

```
class DLLItem {
    public unique Object data;
    public shared DLLItem prev;
    public shared DLLItem next;
}

public class DLL {
    private shared DLLItem head;

    public void add(unique >> none Object data) : unique {
        shared DLLItem li = new DLLItem();
        this.head.prev = li;
        li.next = this.head;
        li.data = data;
        this.head = li;
    }
}
```



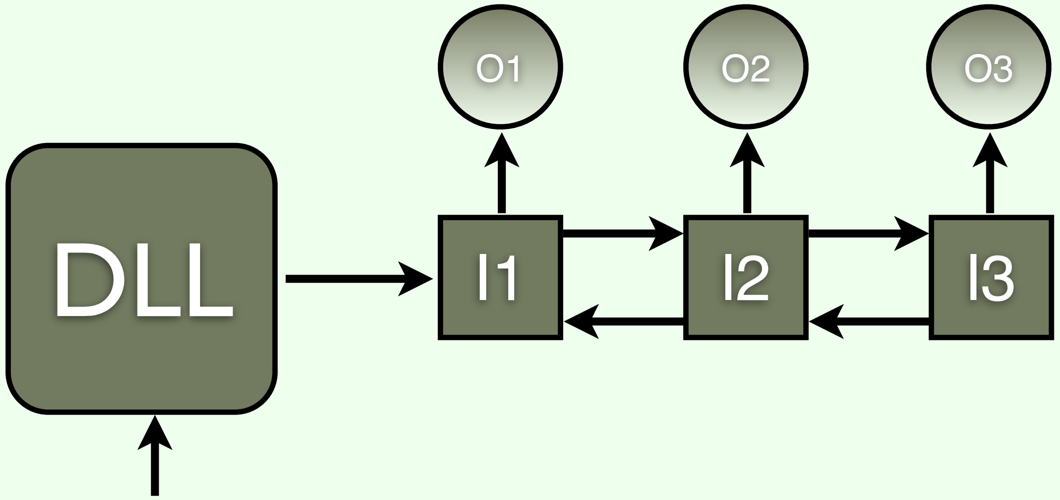
ERROR: Access shared data

Data Group Example

```
class DLLItem {
    public unique Object data;
    public shared DLLItem prev;
    public shared DLLItem next;
}

public class DLL {
    private shared DLLItem head;

    public void add(unique >> none Object data) : unique {
        atomic {
          shared DLLItem li = new DLLItem();
          this.head.prev = li;
          li.next = this.head;
          li.data = data;
          this.head = li;
        }
    }
}
```

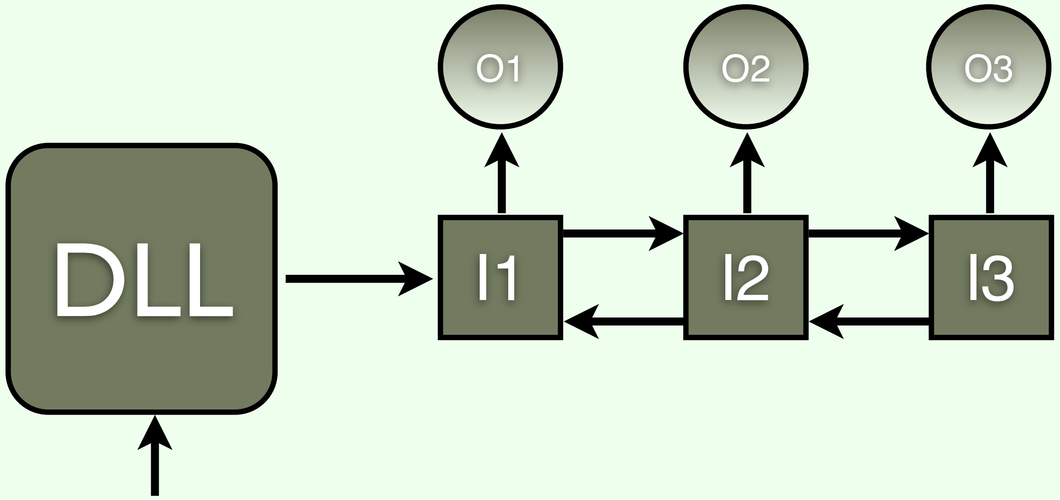


Data Group Example

```
class DLLItem {
    public unique Object data;
    public shared DLLItem prev;
    public shared DLLItem next;
}

public class DLL {
    private shared DLLItem head;

    public void add(unique >> none Object data) : unique {
       atomic {
         shared DLLItem li = new DLLItem();
         this.head.prev = li;
         li.next = this.head;
         li.data = data;
         this.head = li;
       }
    }
}
```



Unique receiver means no aliases

Data Group Example

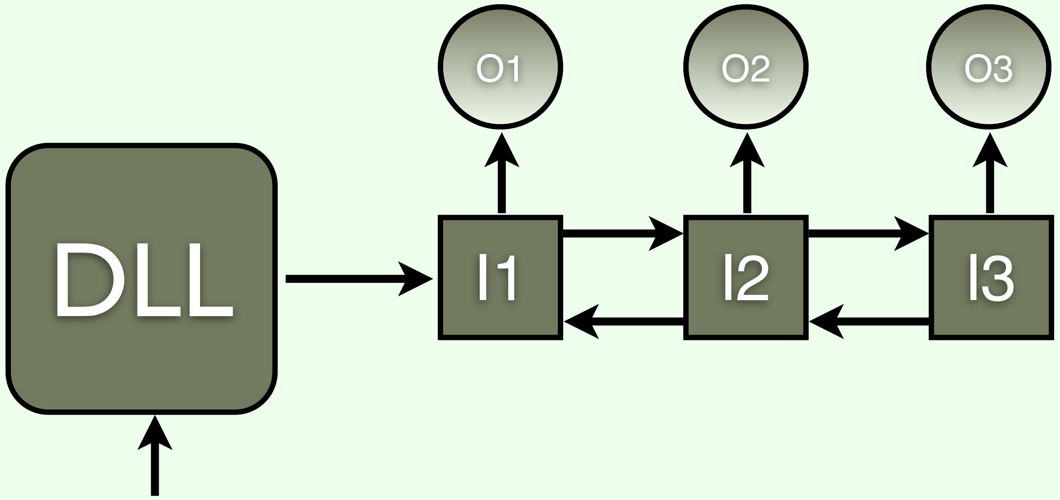
```
class DLLItem    {
    public unique Object data;
    public shared DLLItem    prev;
    public shared DLLItem    next;
}

public class DLL {
    group nodes;
    private shared DLLItem head;

    public void add(unique >> none Object data) : unique {

        shared DLLItem        li = new DLLItem      ();
        this.head.prev = li;
        li.next = this.head;
        li.data = data;
        this.head = li;

    }
}
```



Data Group Example

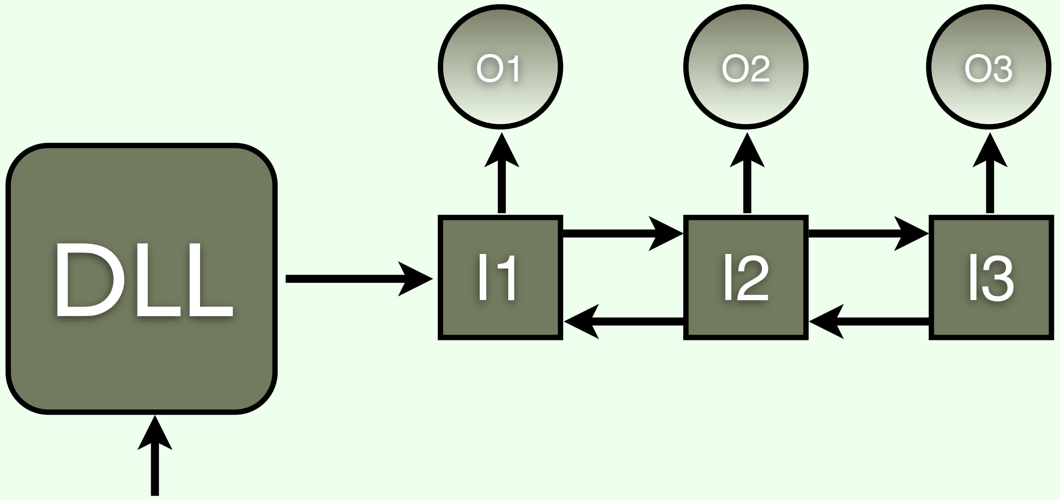
```
class DLLItem<G> {
    public unique Object data;
    public shared DLLItem<G> prev;
    public shared DLLItem<G> next;
}

public class DLL {
    group nodes;
    private shared DLLItem head;

    public void add(unique >> none Object data) : unique {

        shared DLLItem        li = new DLLItem      ();
        this.head.prev = li;
        li.next = this.head;
        li.data = data;
        this.head = li;

    }
}
```



Data Group Example

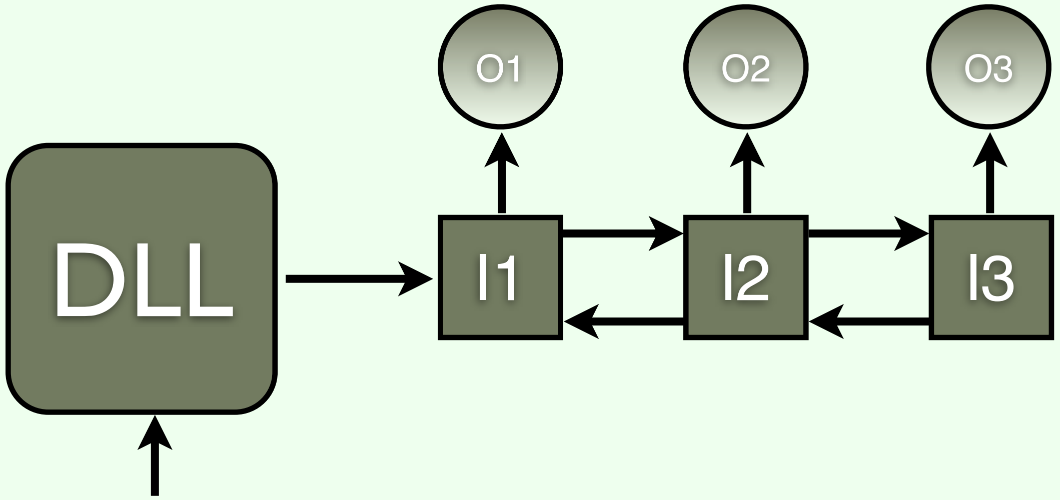
```
class DLLItem<G> {
    public unique Object data;
    public shared DLLItem<G> prev;
    public shared DLLItem<G> next;
}

public class DLL {
    group nodes;
    private shared DLLItem head;

    public void add(unique >> none Object data) : unique {

        shared DLLItem<nodes> li = new DLLItem<nodes>();
        this.head.prev = li;
        li.next = this.head;
        li.data = data;
        this.head = li;

    }
}
```



Data Group Example

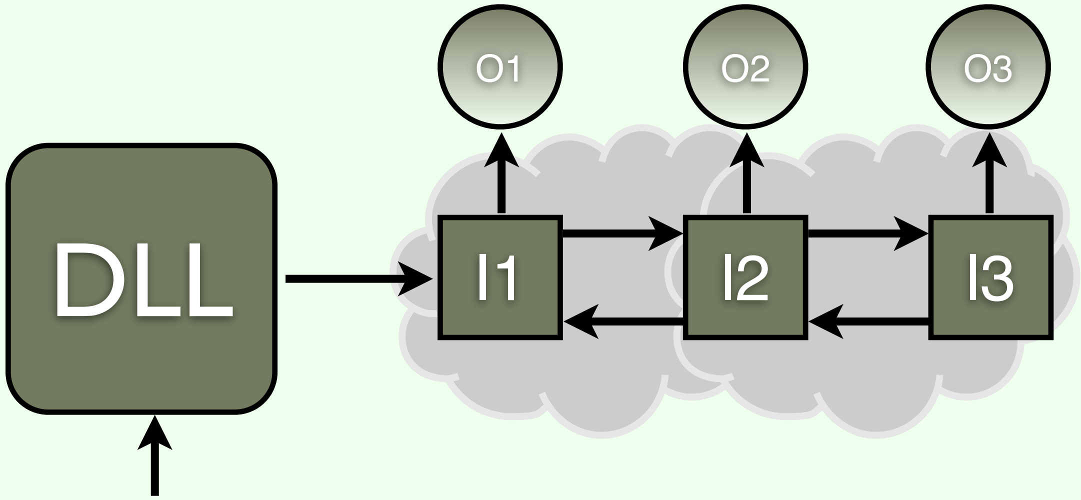
```
class DLLItem<G> {
    public unique Object data;
    public shared DLLItem<G> prev;
    public shared DLLItem<G> next;
}

public class DLL {
    group nodes;
    private shared DLLItem head;

    public void add(unique >> none Object data) : unique {

        shared DLLItem<nodes> li = new DLLItem<nodes>();
        this.head.prev = li;
        li.next = this.head;
        li.data = data;
        this.head = li;

    }
}
```

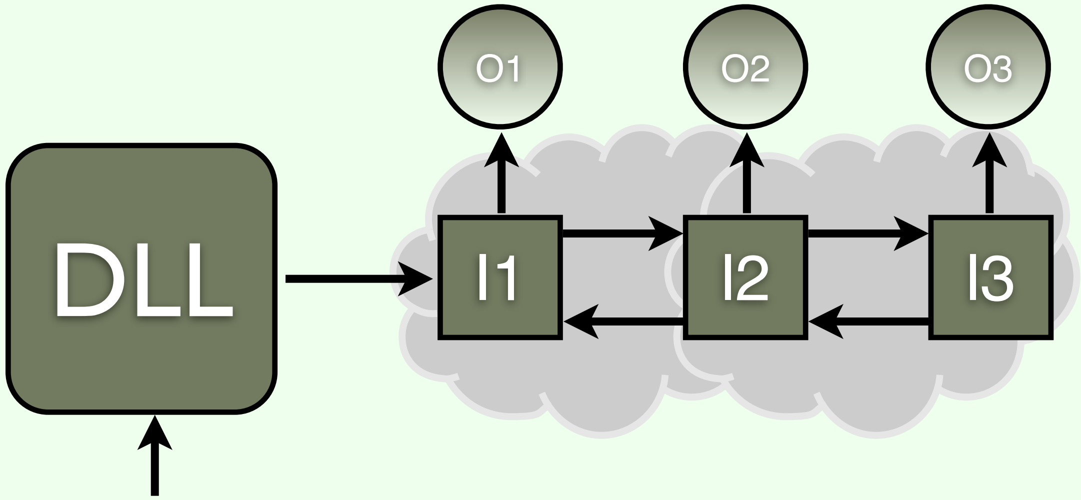


Data Group Example

```
class DLLItem<G> {
    public unique Object data;
    public shared DLLItem<G> prev;
    public shared DLLItem<G> next;
}

public class DLL {
    group nodes;
    private shared DLLItem head;

    public void add(unique >> none Object data) : unique {
       unpack {
         shared DLLItem<nodes> li = new DLLItem<nodes>();
         this.head.prev = li;
         li.next = this.head;
         li.data = data;
         this.head = li;
       }
    }
}
```



Data Group Example

```
public void add(unique >> none Object data) : unique {
   unpack {
      ...
      li.data = data;
   }

}
```

Data Group Example

```
public void add(unique >> none Object data) : unique {
    // this: unique        data: unique
    unpack {

        ...

        li.data = data;

    }

}
```

Data Group Example

```
public void add(unique >> none Object data) : unique {

    unpack {
        // this: unique     this.nodes: exclusive      data: unique
        ...

        li.data = data;

    }


}
```

Data Group Example

```
public void add(unique >> none Object data) : unique {

  unpack {

    ...
    // this: unique    this.nodes: exclusive      data: unique
    li.data = data;

  }


}
```

Data Group Example

```
public void add(unique >> none Object data) : unique {

    unpack {

        ...

        li.data = data;
        // this: unique    this.nodes: exclusive
    }


}
```

Data Group Example

```
public void add(unique >> none Object data) : unique {
    unpack {
        ...
        li.data = data;
    }
    // this: unique
}
```

Data Group Example

```
public void add(unique >> none Object data) : unique {
   unpack {
      ...
      li.data = data;
   }

}
```

Progress so far

µÆMINIUM

- core-calculus based on group permissions
- **concurrent-by-default** type system
- soundness proof for absence of **race conditions** (cf. ‘safety’ hypothesis)

Dataflow Runtime

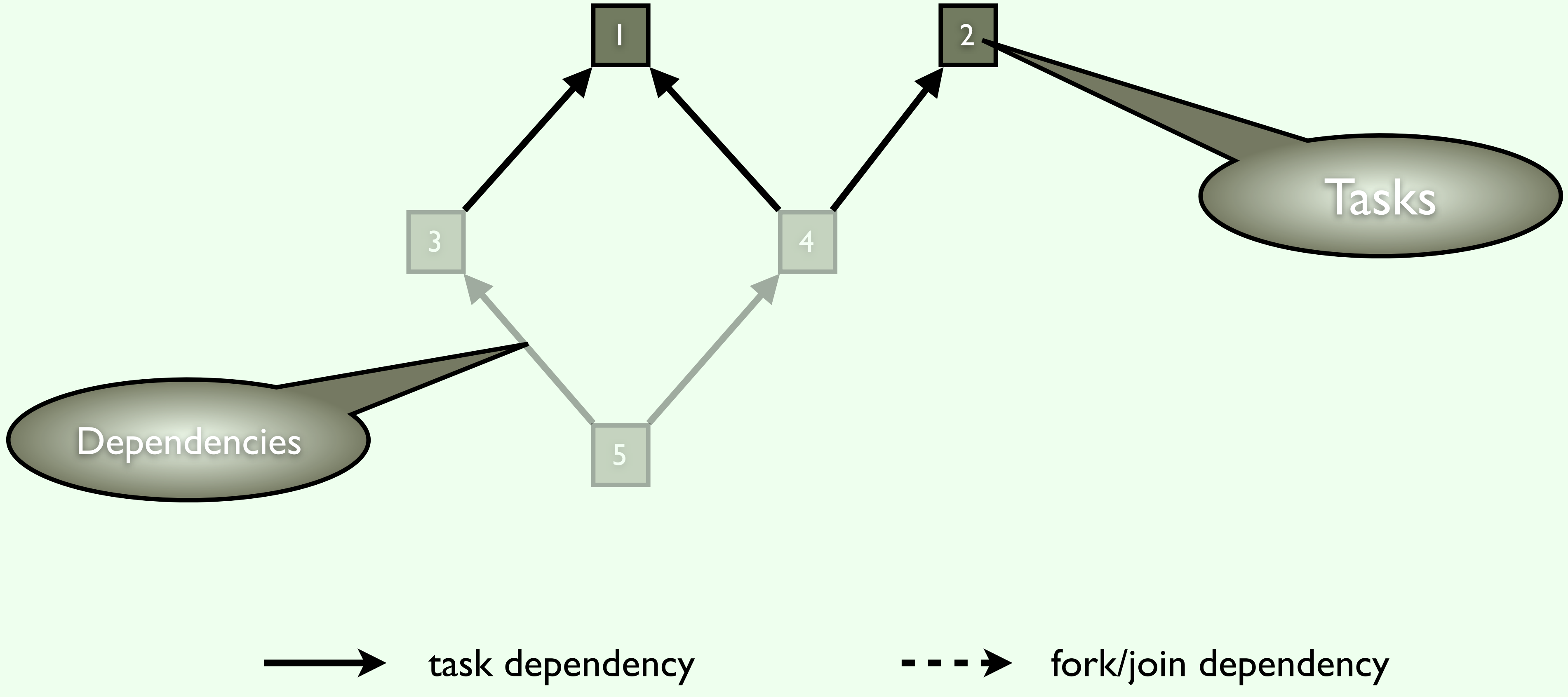
- data flow runtime system for ÆMINIUM
- **task** based runtime system for **dataflow** and **fork/join** parallelisms
- support for **locks** and **STM**
- **dynamic detection** of **deadlocks** (for the lock based approach)

Dataflow Runtime

- support for 3 kinds of tasks
- **Non-Blocking** -- computation intensive
- **Blocking** -- I/O tasks
- **Atomic** -- task that require protection

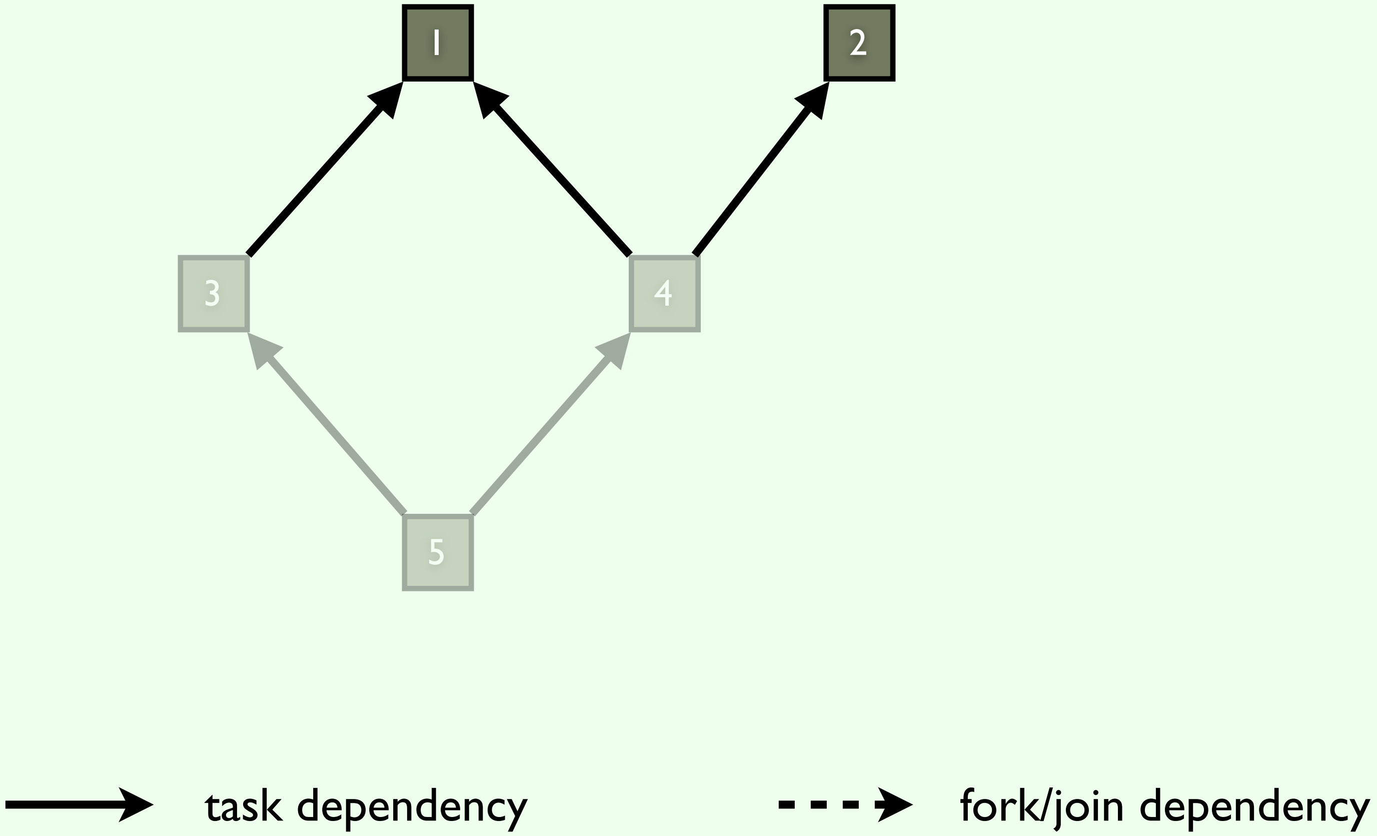
Dataflow Runtime

- data flow runtime system for ÆMINIUM
- task based support for **dataflow** and **fork/join** parallelisms



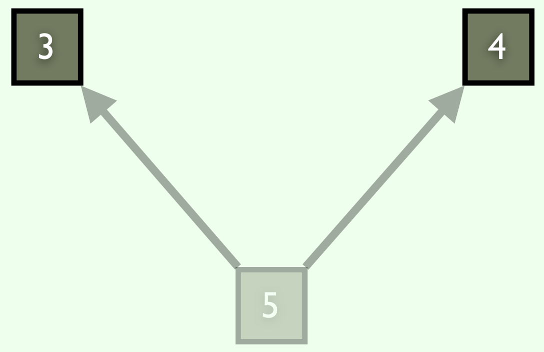
Dataflow Runtime

- data flow runtime system for ÆMINIUM
- task based support for **dataflow** and **fork/join** parallelisms



Dataflow Runtime

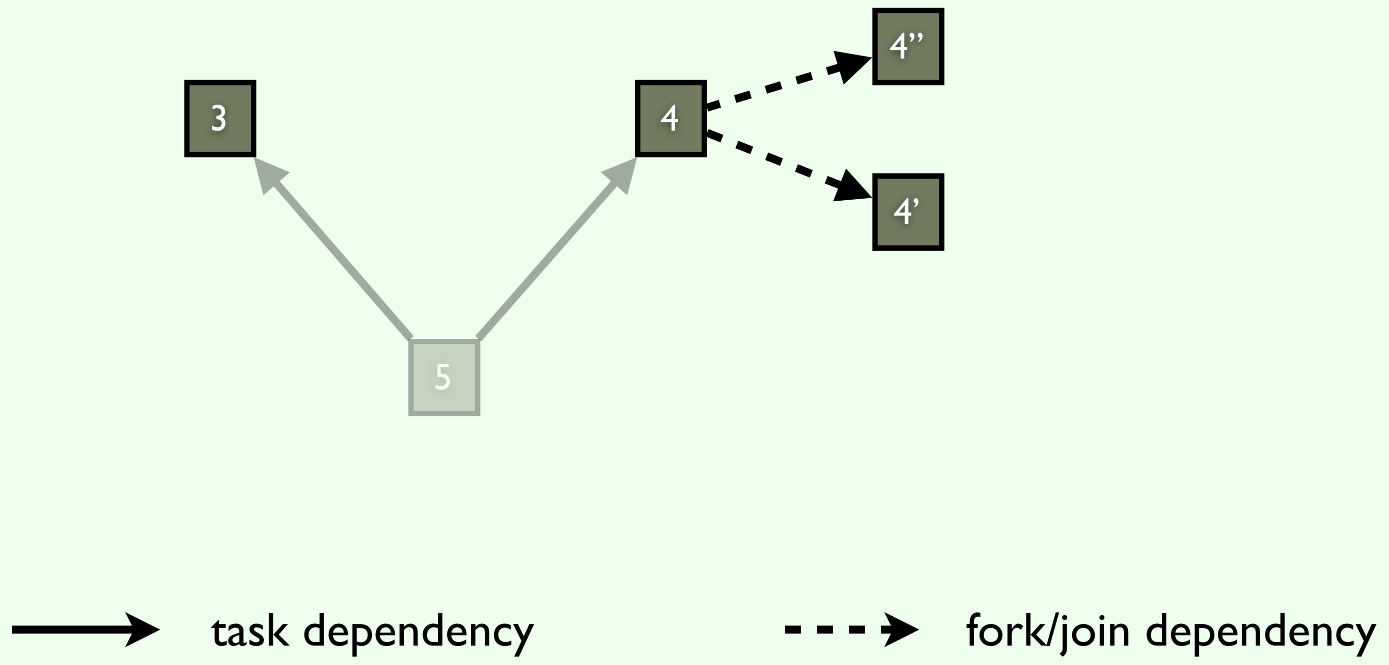
- data flow runtime system for ÆMINIUM
- task based support for **dataflow** and **fork/join** parallelisms



⟶ task dependency ⇢ fork/join dependency

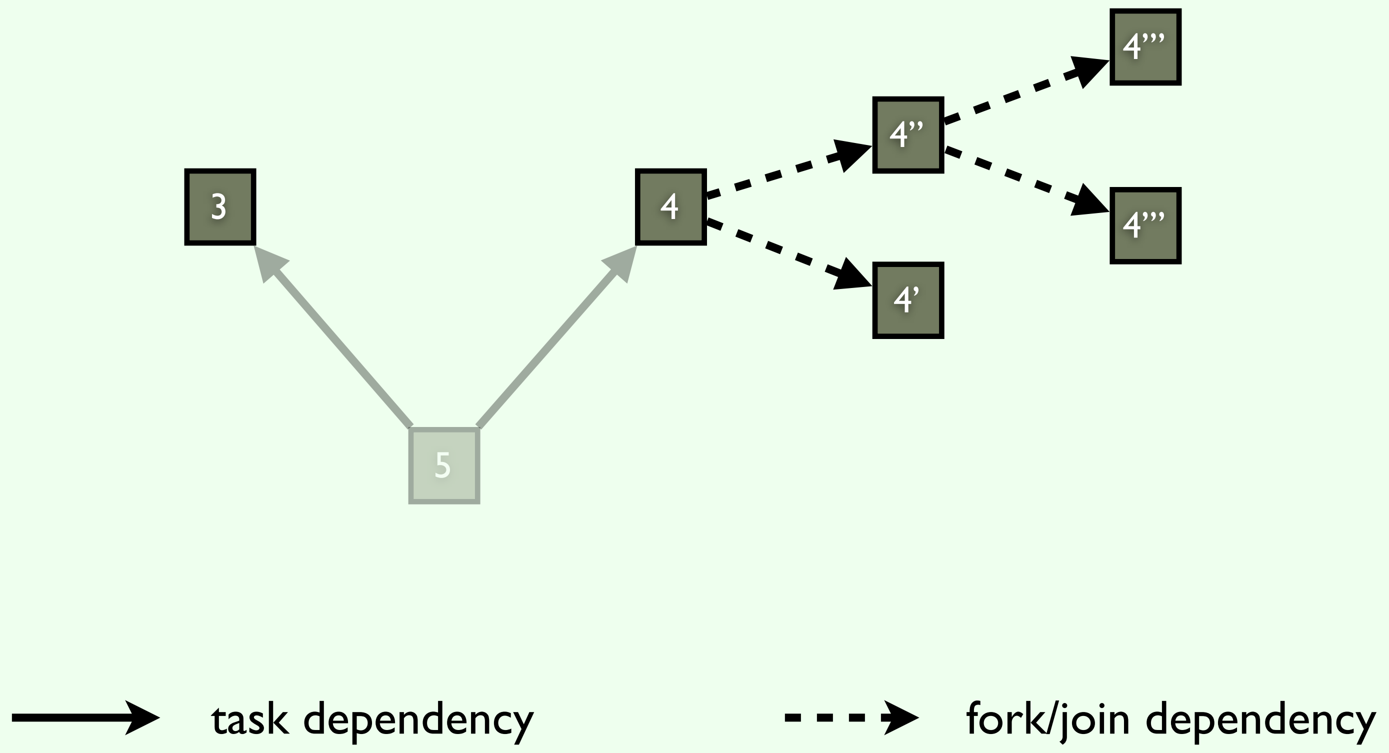
Dataflow Runtime

- data flow runtime system for ÆMINIUM
- task based support for **dataflow** and **fork/join** parallelisms



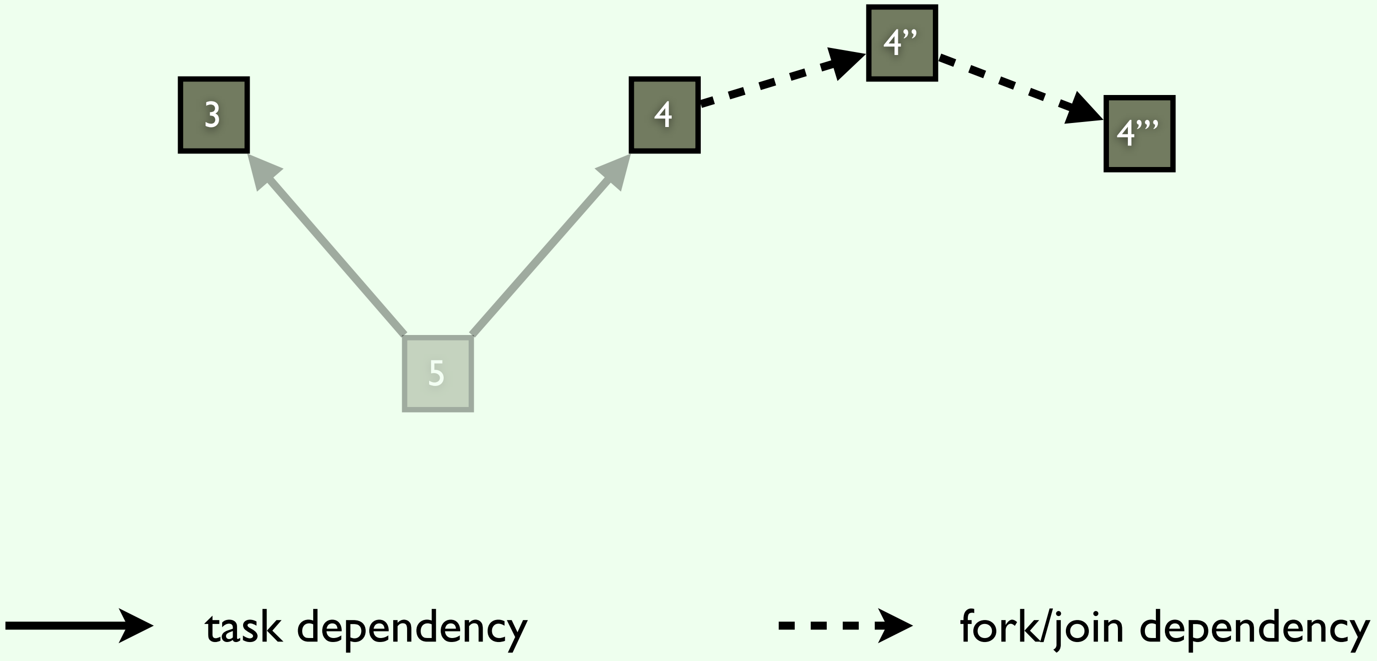
Dataflow Runtime

- data flow runtime system for ÆMINIUM
- task based support for **dataflow** and **fork/join** parallelisms



Dataflow Runtime

- data flow runtime system for ÆMINIUM
- task based support for **dataflow** and **fork/join** parallelisms



Dataflow Runtime

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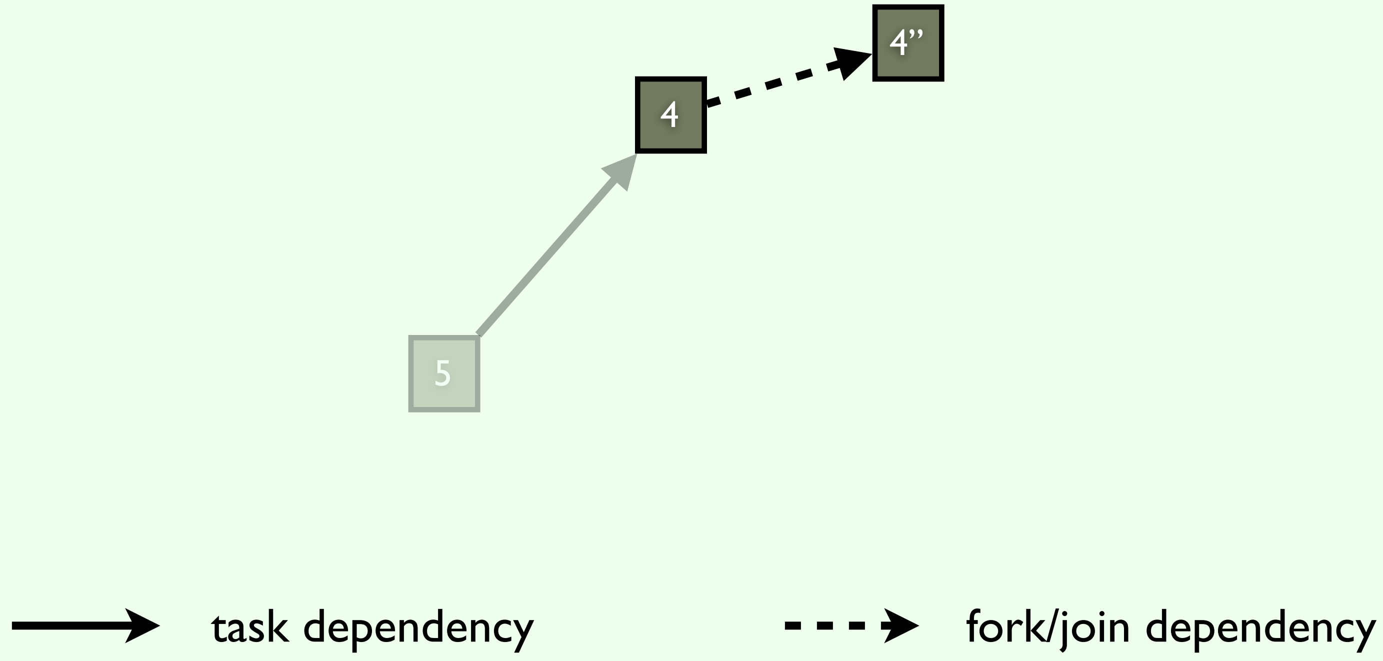
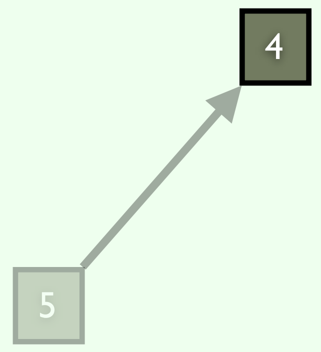


Dataflow Runtime

- data flow runtime system for ÆMINIUM
- task based support for **dataflow** and **fork/join** parallelisms



→ task dependency ⇢ fork/join dependency

Dataflow Runtime

- data flow runtime system for ÆMINIUM
- task based support for **dataflow** and **fork/join** parallelisms

Dataflow Runtime

- data flow runtime system for ÆMINIUM
- task based support for **dataflow** and **fork/join** parallelisms

⟶ task dependency ⇢ fork/join dependency

Dataflow Runtime Performance Evaluation

- compare performance to Java’s fork/join framework
    - run micro benchmarks used by the fork/join paper
    - ÆMINIUM runtime about 35% slower

Dataflow Runtime “Atomic” Evaluation

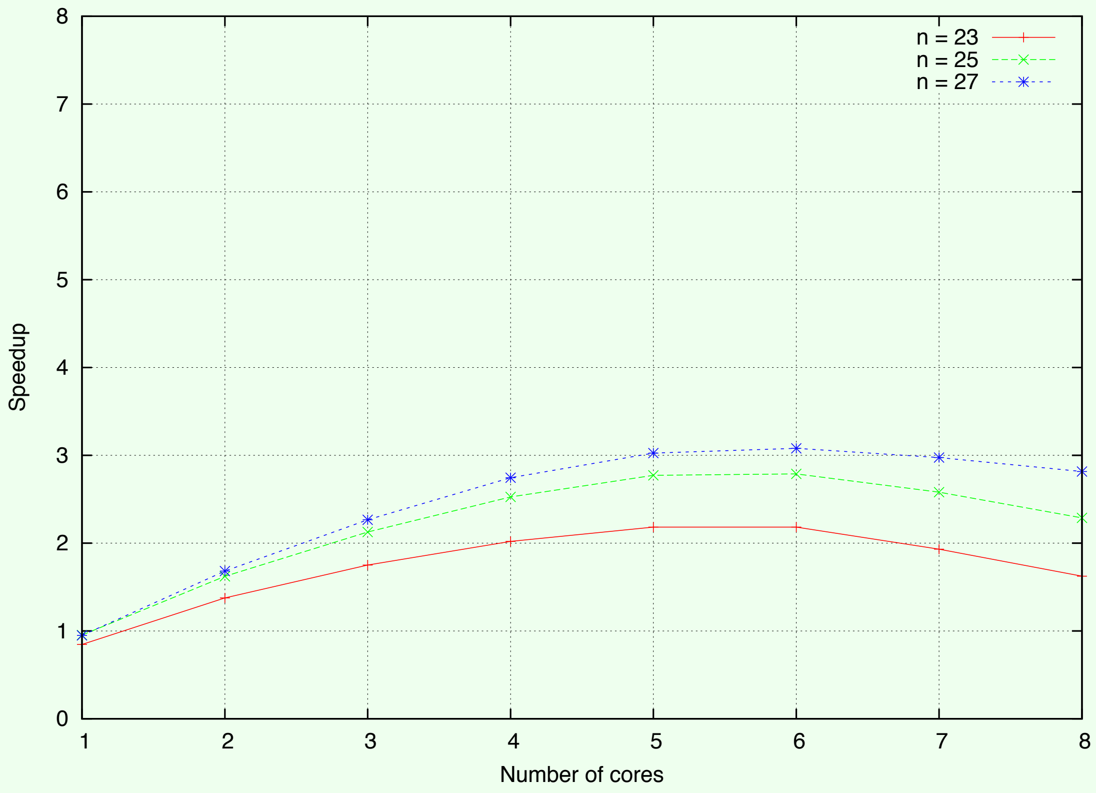
- compare worst, best and intermediate case
  - one global lock vs one lock per object
  - access single object vs multiple objects
  - read vs write
- the locking based implementation outperformed STM based implementation in almost all cases

Proof of Concept

- Master thesis of Manuel Mohr
- hand generated AST with type information
- each method call becomes a task
- showed principle feasibility

Proof of Concept

- performance improvements
- more optimize systems
- dynamic/static load balancing



Road ahead ...

Language Implementation

- implementing ÆMINIUM in Plaid
- Plaid has built-in support for permissions
- limited type checker for Plaid
  (lambda support is still missing)

Language Implementation

1. add ÆMINIUM to Plaid language/parser
2. extend Plaid typechecker with data groups
3. extend Plaid infrastructure to compute dataflow graph based on permission flow
4. extend Plaid code generator to produce parallel code

Approach

- 1st milestone
  - extend Plaid to compute permission flow and parallelize code (no data groups)
- 2nd milestone
  - extend Plaid with data groups
- Evaluate system

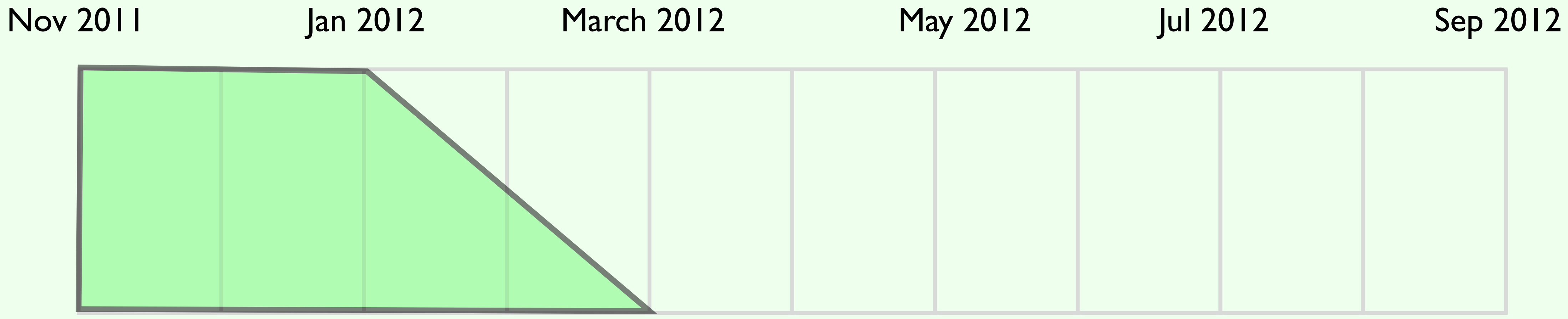
Evaluation

- conducting multiple case studies
  - evaluating performance (cf. **efficiency** hypothesis)
  - evaluating practicality (cf. **practical** hypothesis)

Evaluation

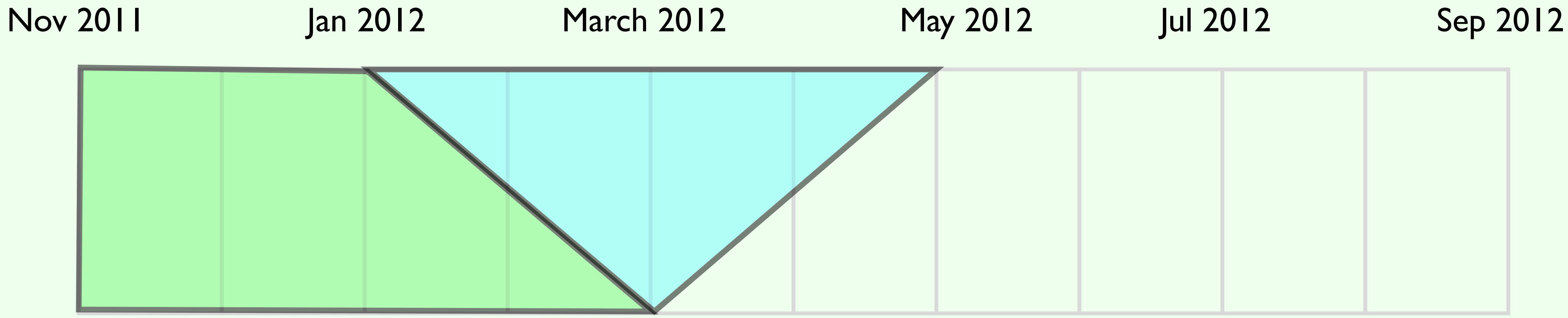
- selection of case studies
    - use applications with known parallel/ concurrency characteristics
    - use representative applications
        - existing real-world applications
        - existing benchmarks (SPLASH, SPEC, DaCapo, etc)
- rewrite applications in ÆMINIUM/Plaid

Time Line



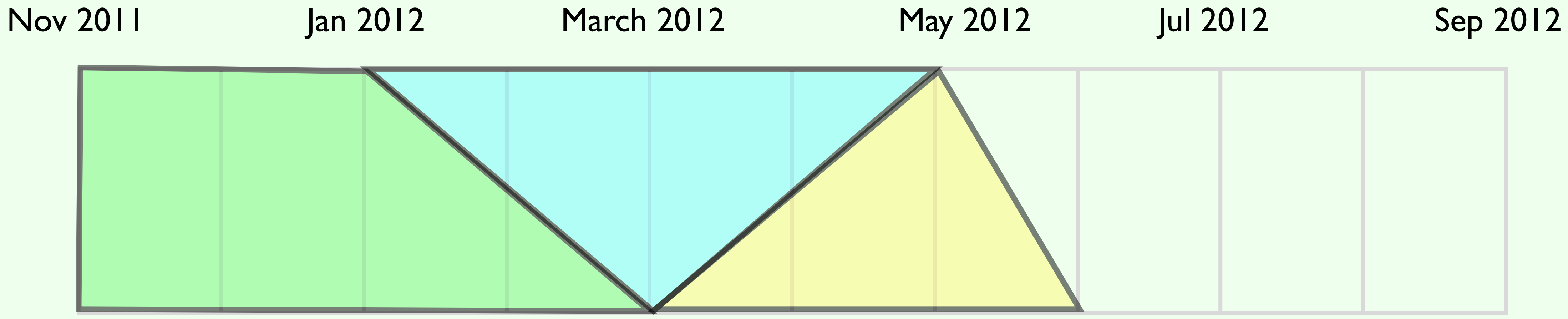
1st Milestone
permission only implementation

Time Line



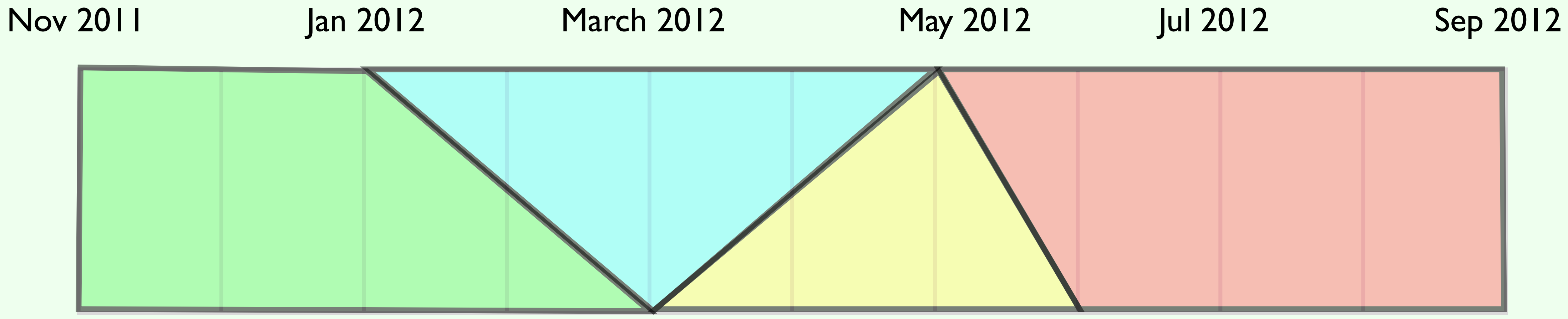
2nd Milestone
data group implementation

Time Line



Evaluation

Time Line



writing thesis

Risks

- Slow progress in Plaid
  - omit unnecessary features
  - parallelize/overlap work
  - 2 stage approach

Risks

- Granularity issues
  - implement optimization techniques (e.g., task merging, flattening, etc)
  - use dynamic load-balancing to avoid generation of "useless" tasks

Risks

- Lack of parallelism
  - no silver bullet
  - ensure that we do not pay extra in the case there is no parallelism

Thanks for the Attention!

Questions?