PLAID:
A Resource-Based Language

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Resource Composition

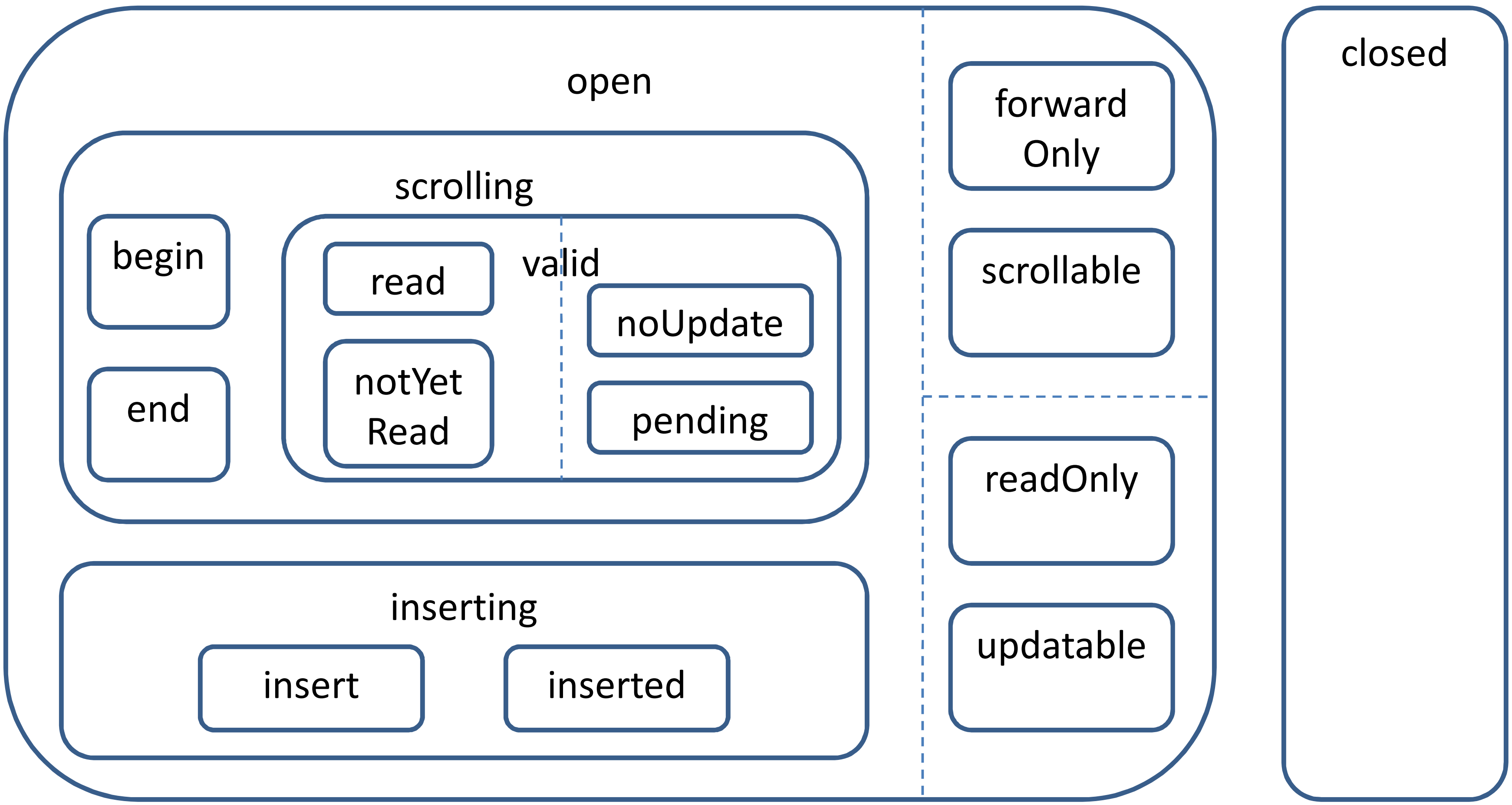
- Modern programming – composition of programs from parts
  - Less emphasis on algorithms / data structures
  - Challenge: is that composition correct?

- Resource composition both important and difficult
  - Resource: stateful object whose use is constrained in some way
  - Example constraints: initialization, cleanup, lifecycle, coordination among threads
  - Even more challenging in a concurrent environment

- Scientific question
  - Could designing a language around resources help us to compose software more correctly and effectively, in a concurrent setting?

Resources are Complex

Java Database Connectivity (JDBC) Library State Space



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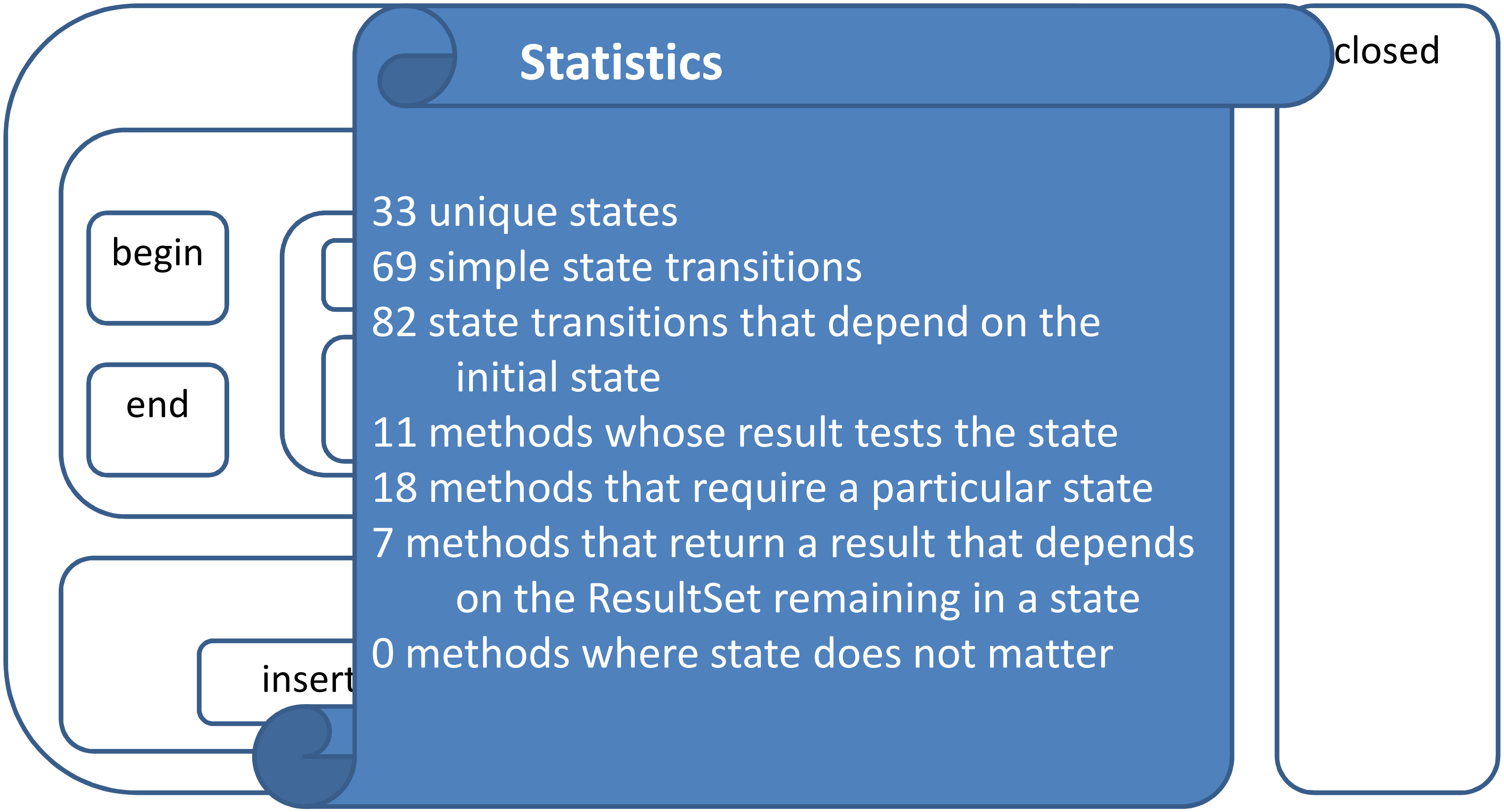
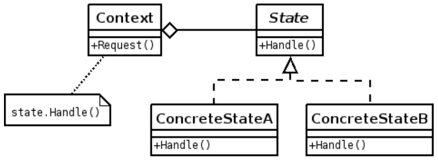


Statistics

- 33 unique states
- 69 simple state transitions
- 82 state transitions that depend on the initial state
- 11 methods whose result tests the state
- 18 methods that require a particular state
- 7 methods that return a result that depends on the ResultSet remaining in a state
- 0 methods where state does not matter

State Use in Practice

- Our empirical study found a substantial portion (~15-20%) of Java classes used or defined a protocol



- Empirically discovered “protocol design patterns”
  - **Initialization** before use – e.g. init(), open(), connect()
  - **Cleanup** – e.g. close()
  - **Non-redundancy** – can only call a method once, e.g. setCause()
  - **Boundary** check – e.g. hasNext()
  - **Marker** – marks a subset of objects with an interface, e.g. immutable collections
  - **Preparation** – e.g. call mark() before reset() on a stream
  - **Matching** – two operations called in a balanced way, e.g. lock/unlock

Related Work: Typestate

- Typestate [Strom and Yemeni ’86]
  - Captures a resource usage protocol as a set of states, with operations for each state
- Prior typestate work
  - Fugue: extension to objects [Deline & Fähndrich ’04]
  - Most systems forbid aliasing, nondeterminism, re-entrancy, concurrency, dynamic tests, flexible inheritance (all common in practice)
  - Very limited experience – only 1 significant case study (ADO.NET)
- Our Plural system had novel approaches to addressing limitations
  - State guarantees; state dimensions; new permission kinds; union and intersection types; re-entrant safe packing; additive conjunction; supertype invariants [OOPSLA’07]; atomicity [OOPSLA ’08]
- Plural is the first demonstrated to scale to real code [ECOOP’09]
  - Specification: JDBC (10 kLOC), Collections, Regular Expressions…
  - Verification: PMD (38 kLOC), Apache Beehive (aliasing challenges)

Roadmap

- Introduction
- Typestate-Oriented Programming
- Plaid's Compositional Object Model
- Parallel by Default Programming / ÆMINIUM
- Conclusion

Typestate-Oriented Programming

A **new programming paradigm** in which:

programs are made up of dynamically created **objects**,

each object has a **typestate** that is **changeable**

and each typestate has an **interface**, **representation**, and **behavior**.

- compare: prior typestate work considered only changing interfaces

Typestate-oriented Programming is embodied in the language

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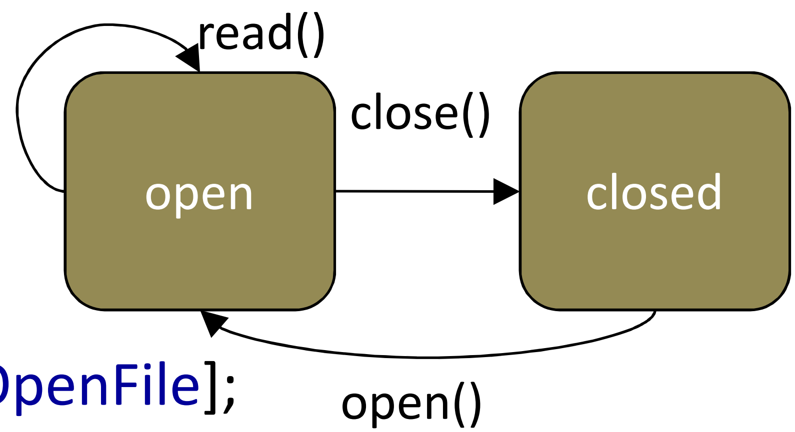
Typestate-Oriented Programming

```
state File {
    val String filename;
}
state ClosedFile = File with {
    method void open() [ClosedFile>>OpenFile];
}
state OpenFile = File with {
    private val CFile fileResource;

    method int read();
    method void close() [OpenFile>>ClosedFile];
}
```

State transition



Different representation

New methods

Implementing Typestate Changes

```
method void open() [ClosedFile>>OpenFile] {
    this <- OpenFile {
        fileResource = fopen(filename);
    }
}
```

Typestate change primitive

Values must be specified for each new field

:

Why Typestate in the Language?

- The world has state – so should programming languages
  - egg -> caterpillar -> butterfly; sleep -> work -> eat -> play; hungry <-> full
- Language influences thought [Boroditsky '09]
  - Language support encourages engineers to **think** about states
    - Better designs, better documentation, more effective reuse
- Improved library specification and verification
  - Typestates define when you can call read()
  - Make constraints that are only implicit today, explicit
- Expressive modeling
  - If a field is not needed, it does not exist
  - Methods can be overridden for each state
- Simpler reasoning
  - Without state: fileResource non-**null** if File is open, **null** if closed
  - With state: fileResource always non-**null**
    - But only exists in the FileOpen state

Checking Typestate

```
method void openHelper(ClosedFile>>OpenFile aFile) {
    aFile.open();
}

method int readFromFile(ClosedFile f) {
    openHelper(f);
    val x = computeBase() + f.read();
    f.close();
    return x;
}
```

This method transitions the argument from ClosedFile to OpenFile

Must leave in the ClosedFile state

Use the type of openHelper

f is open so read is OK

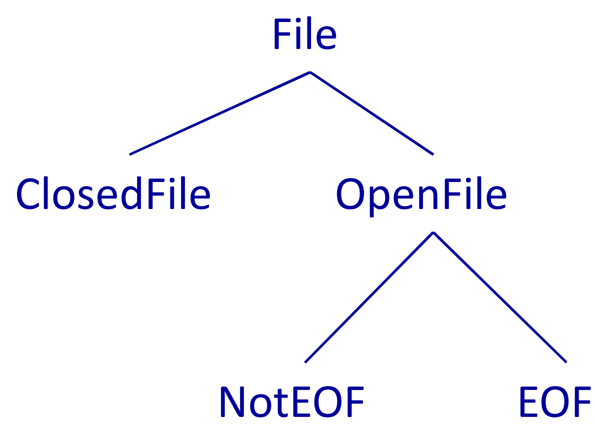
Correct postcondition; f is in ClosedFile

Question: How do we know computeBase doesn't affect the file (thorugh an alias)?

Typestate Permissions

- **unique** OpenFile
  - File is open; no aliases exist
  - Default for mutable objects
- **immutable** OpenFile
  - Cannot change the File
    - Cannot close it
    - Cannot write to it, or change the position
  - Aliases may exist but do not matter
  - Default for immutable objects

[Chan et al. ’98]



- **shared** OpenFile@NotEOF [OOPSLA ’07]
  - File is aliased
  - File is currently not at EOF
    - Any function call could change that, due to aliasing
  - It is forbidden to close the File
    - OpenFile is a *guaranteed* state that must be respected by all operations through all aliases
- **none** – no permission

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Object Model Goals

- Support for object-oriented and functional programming
  - Objects and subtyping; functions and type abstraction
- Abstract, flexible interfaces
  - Support after-the-fact interface extraction without modifying code
    - compare Java: must modify classes to implement the new interface
- Clean, effective code reuse
  - Same level of convenience as multiple inheritance
  - Avoid problems like name conflicts, unintentional open recursion
- Flexibility
  - Ways to escape from type system when it is too strict
- Information hiding
  - Avoid violations of abstraction
    - e.g. instanceof on a datatype that's not conceptually a tagged union

Functional Programming Support

```
val ADT = new {
    type set = List;
    method set<T> union(
            set<T> s1, set<T> s2) {
        s1.appendList(s2);
    }
} as {
    type set <: { type E; };
    val union: set<T> * set<T> -> set<T>
}
```

```
method List<U>
    map('T -> 'U f)(List<T> lst) {
    match(lst) {
        case Cons(e,rest) =>
            makeCons(f(e), map(f)(rest))
        case Nil => Nil
    }
}

… map (fn (int x) => x + 1) (myIntList) …
```

Structural Types

```
type IntCollection = {
    method IntCollection add(int newInt);
}

type IntList = {
    method IntList add(int newInt);
    method int get(int index);
}

IntList list = makeMyList();
IntCollection coll = list;      // implicit structural subtyping
```

Safe Code Reuse via Composition

```
state AbstractCollection = {
    method void addAll(Collection other) {
        other.do (fn (int x) => add(x))
    }
    requires open method void add();
}
```

Reusable abstract state

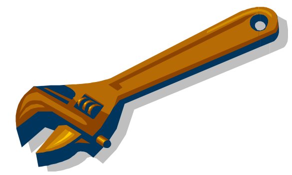
Selective open recursion [SAVCBS '04]: open recursion is only used in calls to methods marked **open**. The **open** keyword documents that subclasses can override self-calls to this method. Other methods can be overridden but self calls are unaffected.

```
state LinkedList = AbstractCollection[add->addLast] with {
    method void add() { … }
}
```

Trait element renaming

Trait-based composition

Static & Dynamic Checking in Plaid



- Typestate and permissions express *design intent*
  - Typechecking verifies intent statically
  - But sometimes static checking fails, even for OK programs
  - Need to have dynamic checks as a fallback
- Principle
  - All assertions about typestate and permissions can be checked either statically or dynamically
- Features
  - Gradual types [Siek and Taha '06]
    - can omit some types, statically check as much as possible
  - Casts to types, states, and permissions
- Research questions
  - How does gradual typing generalize to permissions?
  - How to check casts to **unique**?

Information Hiding Challenges: Dynamic Types and Pattern Matching

```
set = new Collection with {
    val List<E> members;
    method Set<E> union(Set<E> other);
} as Collection with {
     method Set<E> union(Set<E> other);
}

dynamic dset = set;      // dynamic typing
dset.members.add(e); // FAIL at run time
```

```
type TestMember = {
    boolean isMember(E e); }
state List = { … }
state ArrayList case of List = { … }

List myList = new ArrayList{};
// match OK – ArrayList a case of List
match (myList) {
    case ArrayList al { … }
}

TestMember tm = myList;
// compile-time error: TestMember
// does not support case analysis
match (tm) { … }
```

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Demonstration

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  - Plaid's instantiation of the ÆMINIUM project
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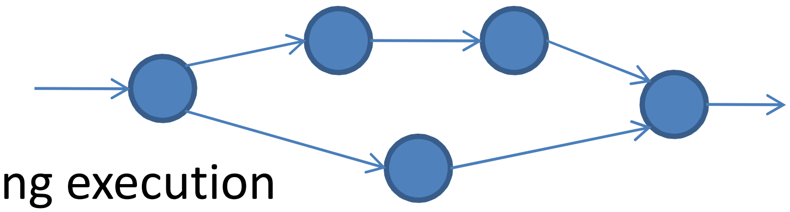
Explicit Dependencies in Plaid

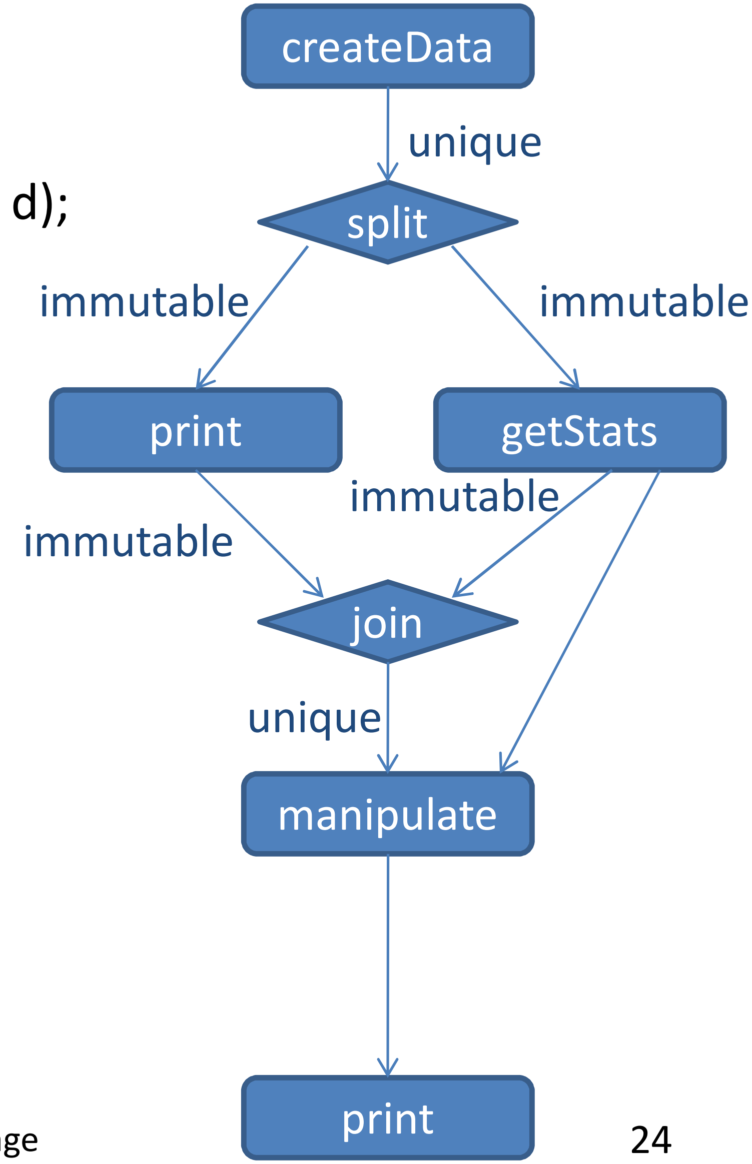


- Concurrency is a major challenge
  - Avoiding race conditions, understanding execution
- Inspiration: functional programming is “naturally concurrent”
  - Up to data dependencies in program
- Idea: use permissions to construct dataflow graph
  - Easier to track dependencies than all possible concurrent executions
  - Functional programming passes data explicitly to show dependencies
  - For stateful programs, we **pass permissions explicitly** instead
- Consequence: stateful programs can be naturally concurrent
  - Furthermore, we can provide strong reasoning about correctness

Features: Sharing and Dependencies

method unique Data createData();
method void print(**immutable** Data d);
method unique Stats getStats(**immutable** Data d);
method void manipulate(**unique** Data d,
                                        immutable Stats s);

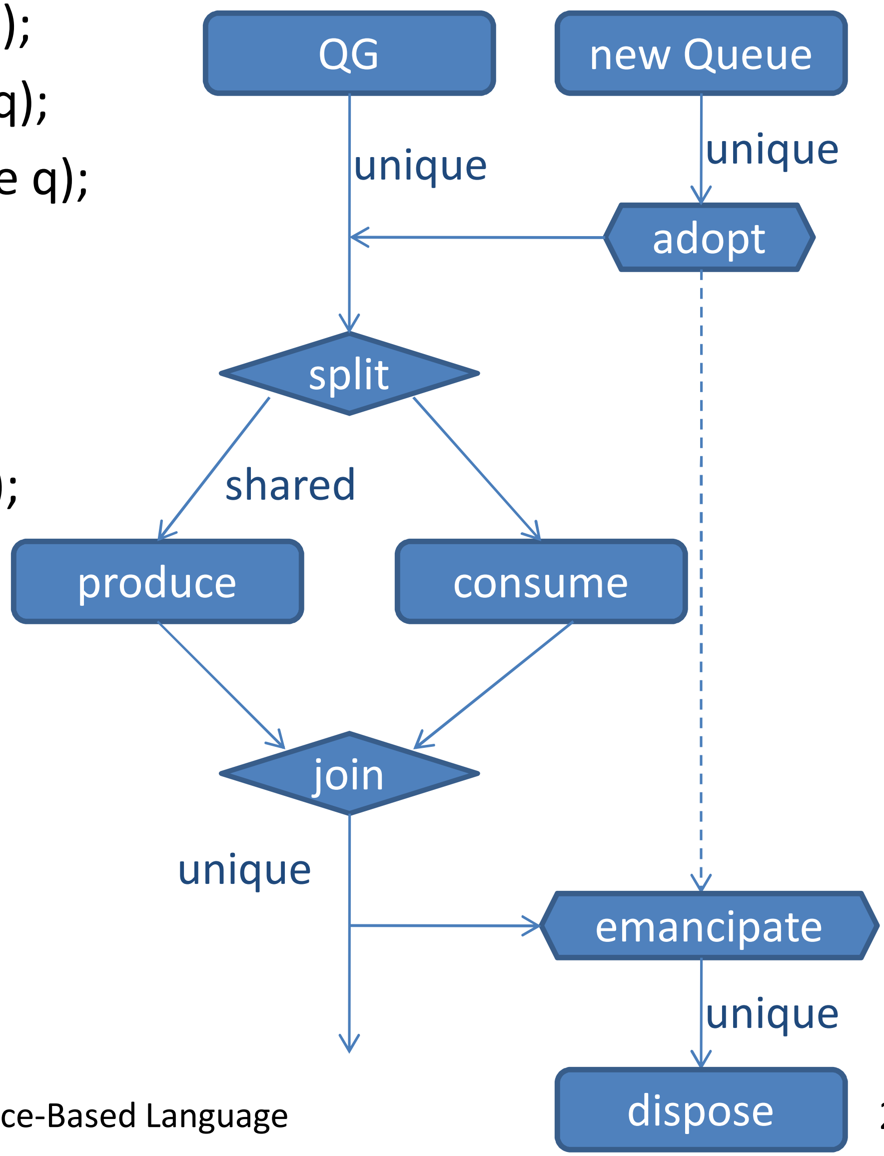
val d = createData();
print(d);
val s = getStats(d);
manipulate(d, s);
print(d);



Features: Sharing and Dependencies

```
method void produce(‘QG Queue q);
method void consume(‘QG Queue q);
method void dispose(unique Queue q);

group QG;
val QG Queue q = new Queue;
split QG: produce(q) || consume(q);
q.dispose();
```



Consequences: Safe Concurrency

- Programmers think only about dependencies
  - Move away from a sequential model
- Programs execute in parallel by default
  - Execution is deterministic except for uses of **split**
- Compatible with shared state, nondeterminism when needed
  - Shared state is tracked with permissions
  - Non-determinism is explicit (in **split** blocks)
  - Non-determinism is scoped to a part of the program and to a specific group of shared data
- Reasoning support
  - Consistent synchronization
  - Typestate protocol verification
  - Synchronization granularity (sufficient to ensure typestate)

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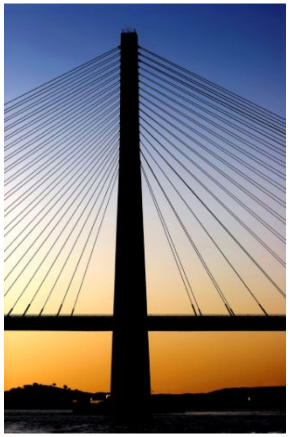
A Bridge to Existing Languages



- Familiarity
  - use Java syntax wherever possible
  - when no clear language design choice, use Java's
    - fix some glaring problems like nulls
      (what Hoare calls his $1 billion mistake)
- Compatibility
  - compile to platforms, like the JVM, that have good existing libraries

Current Plaid Language Research

• Core type system	Darpan Saini, Joshua Sunshine
• Object model	Karl Naden
• Typestate model	Filipe Militão, Luís Caires (FCT)
• Gradual typing	Roger Wolff, Ron Garcia, Eric Tanter (U. Chile)
• Concurrency	Sven Stork, Paulo Marques (U. Coimbra)
• Web programming	Joshua Sunshine
• Permission parameters	Nels Beckman
• Compilation/typechecking	Karl Naden, Joshua Sunshine, Mark Hahnenberg, Sven Stork

The Plaid Language

- Supports programming with resources
  - First-class abstractions for characterizing state
  - Naturally concurrent execution
  - Practical mix of static & dynamic checking
- Opens a new subfield of research
  - Languages based on changeable states and permissions
- Work in progress
  - Compiler implemented (in Java, for now)
  - Plaid typechecker (in Plaid) underway

http://www.plaid-lang.org/