

Concepts of Object-Oriented Programming

Peter Müller

Chair of Programming Methodology

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ETH zürich

Meeting the Requirements

Cooperating Program Parts with Well-Defined Interfaces

- Objects (data + code)
- Interfaces
- Encapsulation

Classification and Specialization

- Classification, subtyping
- Polymorphism
- Substitution principle

Highly Dynamic Execution Model

- Active objects
- Message passing

Correctness

- Interfaces
- Encapsulation
- Simple, powerful concepts

My Billion Dollar Mistake



“I call it my billion-dollar mistake. It was the invention of the null reference in 1965. [...]

This has led to innumerable errors, vulnerabilities, and system crashes, which have probably caused a billion dollars of pain and damage in the last forty years. [...]

More recent programming languages like Spec# have introduced declarations for non-null references. This is the solution, which I rejected in 1965.” [Hoare, 2009]

8. Initialization

8.1 Simple Non-Null Types

8.2 Object Initialization

8.3 Initialization of Global Data

Main Usages of Null-References

```
class Map {  
    Map next;  
    Object key;  
    Object value;  
  
    Map( Object k, Object v ) {  
        key = k;  
        value = v;  
    }  
}
```

```
void add( Object k, Object v ) {  
    if( key.equals( k ) )  
        value = v;  
    else if( next == null )  
        next = new Map( k, v );  
    else next.add( k, v );  
}  
  
Object get( Object k ) {  
    if( key.equals( k ) ) return value;  
    if( next == null ) return null;  
    return next.get( k );  
}  
}
```

Main Usages of Null-References

```
class Map {  
    Map next;  
    Object key;  
    Object value;  
  
    Map( Object k, Object v ) {  
        key = k;  
        value = v;  
    }  
}
```

null terminates
recursion

```
void add( Object k, Object v ) {  
    if( key.equals( k ) )  
        value = v;  
    else if( next == null )  
        next = new Map( k, v );  
    else next.add( k, v );  
}  
  
Object get( Object k ) {  
    if( key.equals( k ) ) return value;  
    if( next == null ) return null;  
    return next.get( k );  
}  
}
```

Main Usages of Null-References

```
class Map {  
    Map next;  
    Object key;  
    Object value;  
  
    Map( Object k, Object v ) {  
        key = k;  
        value = v;  
    }  
}
```

null terminates
recursion

All fields are
initialized to **null**

```
void add( Object k, Object v ) {  
    if( key.equals( k ) )  
        value = v;  
    else if( next == null )  
        next = new Map( k, v );  
    else next.add( k, v );  
}  
  
Object get( Object k ) {  
    if( key.equals( k ) ) return value;  
    if( next == null ) return null;  
    return next.get( k );  
}  
}
```

Main Usages of Null-References

```
class Map {  
    Map next;  
    Object key;  
    Object value;  
  
    Map( Object k, Object v ) {  
        key = k;  
        value = v;  
    }  
}
```

null terminates
recursion

All fields are
initialized to **null**

```
void add( Object k, Object v ) {  
    if( key.equals( k ) )  
        value = v;  
    else if( next == null )  
        next = new Map( k, v );  
    else next.add( k, v );  
}  
  
Object get( Object k ) {  
    if( key.equals( k ) ) return value;  
    if( next == null ) return null;  
    return next.get( k );  
}  
}
```

null indicates
absence of an
object

Main Usages of Null-References (cont'd)

```
class Map {  
    Map next;  
    Object key;  
    Object value;
```

Most variables
hold non-null
values

```
    Map( Object k, Object v ) {  
        key = k;  
        value = v;  
    }  
}
```

```
void add( Object k, Object v ) {  
    if( key.equals( k ) )  
        value = v;  
    else if( next == null )  
        next = new Map( k, v );  
    else next.add( k, v );  
}
```

```
Object get( Object k ) {  
    if( key.equals( k ) ) return value;  
    if( next == null ) return null;  
    return next.get( k );  
}  
}
```

Non-Null Types

- **Non-null type $T!$** consists of references to T -objects
- **Possibly-null type $T?$** consists of references to T -objects **plus null**
 - Corresponds to T in most languages
- A language designer would choose a default

```
class Map {  
    Map? next;  
    Object! key;  
    Object! value;  
  
    Map( Object! k, Object! v ) {  
        key = k;  
        value = v;  
    }  
  
    ...  
}
```

Type Safety

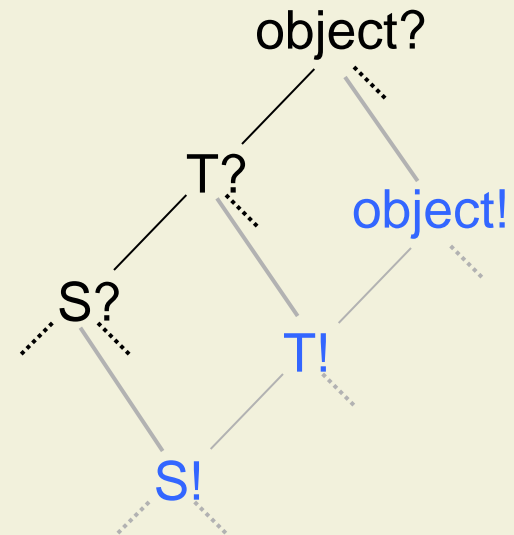
- (Simplified) type invariant:
If the static type of an expression *e* is a non-null type then *e*'s value at run time is different from **null**
- Goal: prevent null-dereferencing statically
 - Require non-null types for the receiver of each field access, array access, method call
 - Analogous to preventing “message not understood” errors with classical type systems

Subtyping and Casts

- The values of a type $T!$ are a proper subset of $T?$
 - $S! <: T!$
 - $S? <: T?$
 - $T! <: T?$

```
class T { ... }
```

```
class S extends T { ... }
```

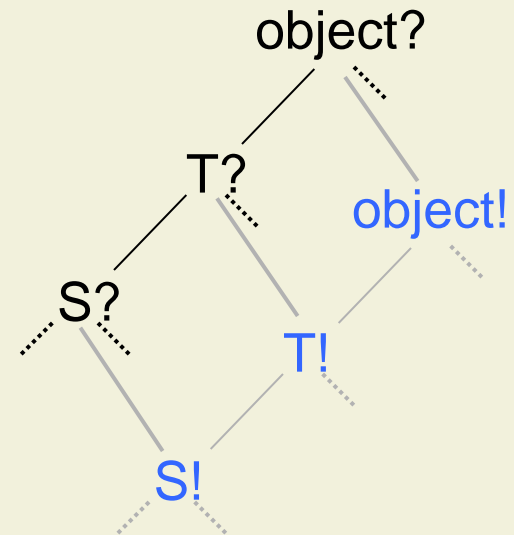


Subtyping and Casts

- The values of a type $T!$ are a proper subset of $T?$
 - $S! <: T!$
 - $S? <: T?$
 - $T! <: T?$

```
class T { ... }
```

```
class S extends T { ... }
```



```
T! nnT = ...
```

```
T? pnT = ...
```

```
S! nnS = ...
```

```
nnT = nnS;
```

```
pnT = pnS;
```

```
pnT = nnT;
```

Subtyping and Casts

- The values of a type $T!$ are a proper subset of $T?$

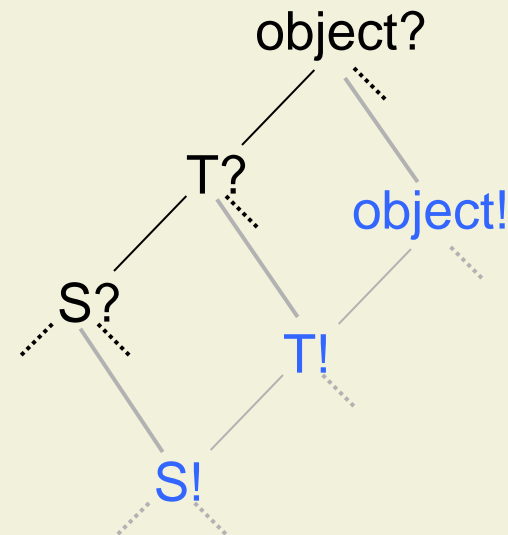
- $S! <: T!$
- $S? <: T?$
- $T! <: T?$

- **Downcasts** from possibly-null types to non-null types **require run-time checks**

```
nnT    = ( T! ) pnT;
nnT    = ( ! ) pnT;
```

```
class T { ... }
```

```
class S extends T { ... }
```



```
T! nnT = ...
T? pnT = ...
S! nnS = ...
```

```
nnT    = nnS;
pnT    = pnS;
pnT    = nnT;
```

Type Rules

- Most type rules of Java remain unchanged
- Additional requirement:
expressions whose value gets dereferenced at run time must have a non-null type
 - Receiver of field access
 - Receiver of array access
 - Receiver of method call
 - Expression of a **throw** statement

```
T! nnT = ...
```

```
T? pnT = ...
```

```
S! nnS = ...
```

```
nnT.f = 5;  
nnS.foo( );
```

```
pnT.f = 5;  
pnT.foo( );
```

Type Rules

- Most type rules of Java remain unchanged
- Additional requirement: expressions whose value gets dereferenced at run time must have a non-null type
 - Receiver of field access
 - Receiver of array access
 - Receiver of method call
 - Expression of a **throw** statement

```
T! nnT = ...  
T? pnT = ...  
S! nnS = ...
```

```
nnT.f = 5;  
nnS.foo( );
```

```
pnT.f = 5;  
pnT.foo( );
```

Compile-time error:
possible
null-dereferencing

Comparing against null

```
class Map {  
  Map? next;  
  
  ...  
  Object? get( Object! k ) {  
    ...  
    Map? n = next;  
    if( n == null ) return null;  
    return n.get( k );  
  }  
}
```

Comparing against null

```
class Map {  
  Map? next;  
  
  ...  
  Object? get( Object! k ) {  
    ...  
    Map? n = next;  
    if( n == null ) return null;  
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  Object? get( Object! k ) {  
  
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    Map? n = next;  
    if( n == null ) return null;  
    return ( ! ) n ).get( k );  
  }  
}
```

Comparing against null

```
class Map {  
  Map? next;  
  
  ...  
  
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Compile-time error:
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class Map {  
  Map? next;  
  
  ...  
  
  Object? get( Object! k ) {  
    ...  
    Map? n = next;  
    if( n == null ) return null;  
    return ( ! ) n ).get( k );  
  }  
}
```

Shorthand for
cast to Map!

Dataflow Analysis

- *Data-flow analysis is a technique for gathering information about the possible set of values calculated at various points in a computer program. A program's control flow graph is used to determine those parts of a program to which a particular value assigned to a variable might propagate.* [Wikipedia]

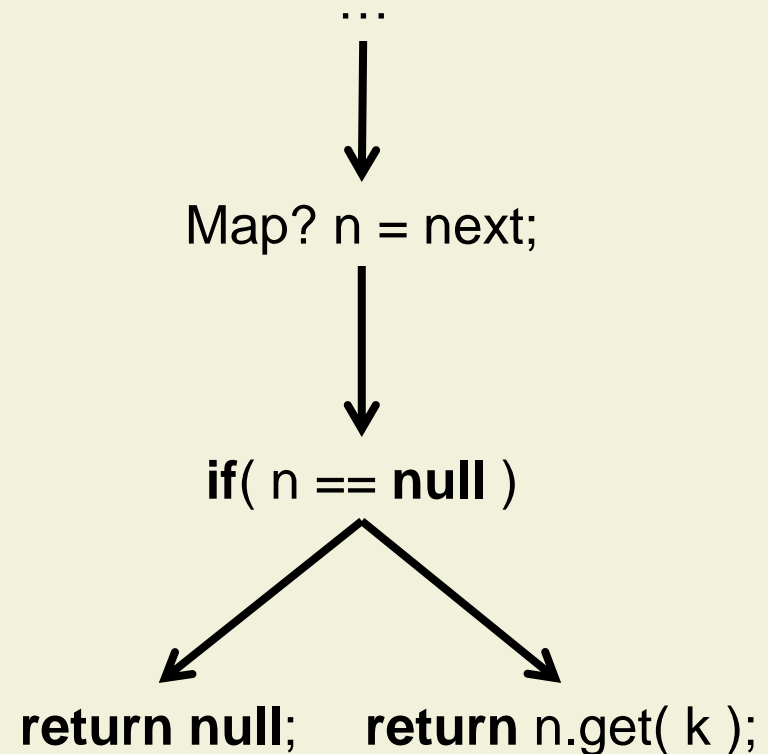
Comparing against null (cont'd)

```
class Map {  
  Map? next;  
  ...  
  Object? get( Object! k ) {  
    ...  
    Map? n = next;  
    if( n == null ) return null;  
    return n.get( k );  
  }  
}
```

Comparing against null (cont'd)

```
class Map {  
  Map? next;  
  ...  
  Object? get( Object! k ) {  
    ...  
    Map? n = next;  
    if( n == null ) return null;  
    return n.get( k );  
  }  
}
```

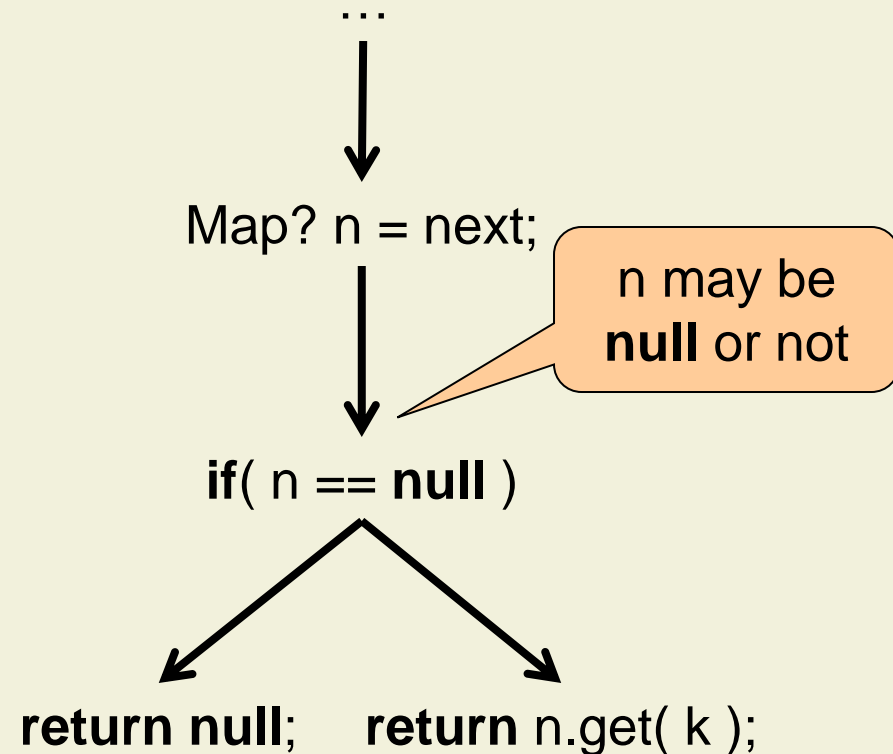
Control Flow Graph



Comparing against null (cont'd)

```
class Map {  
  Map? next;  
  ...  
  Object? get( Object! k ) {  
    ...  
    Map? n = next;  
    if( n == null ) return null;  
    return n.get( k );  
  }  
}
```

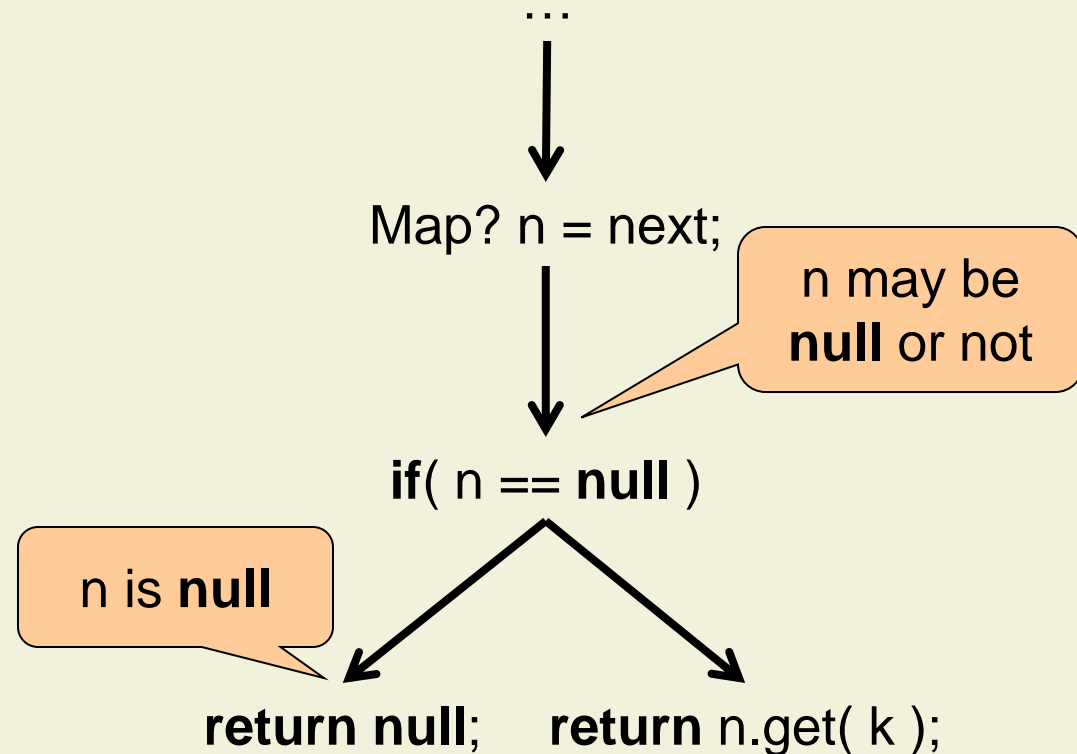
Control Flow Graph



Comparing against null (cont'd)

```
class Map {  
  Map? next;  
  ...  
  Object? get( Object! k ) {  
    ...  
    Map? n = next;  
    if( n == null ) return null;  
    return n.get( k );  
  }  
}
```

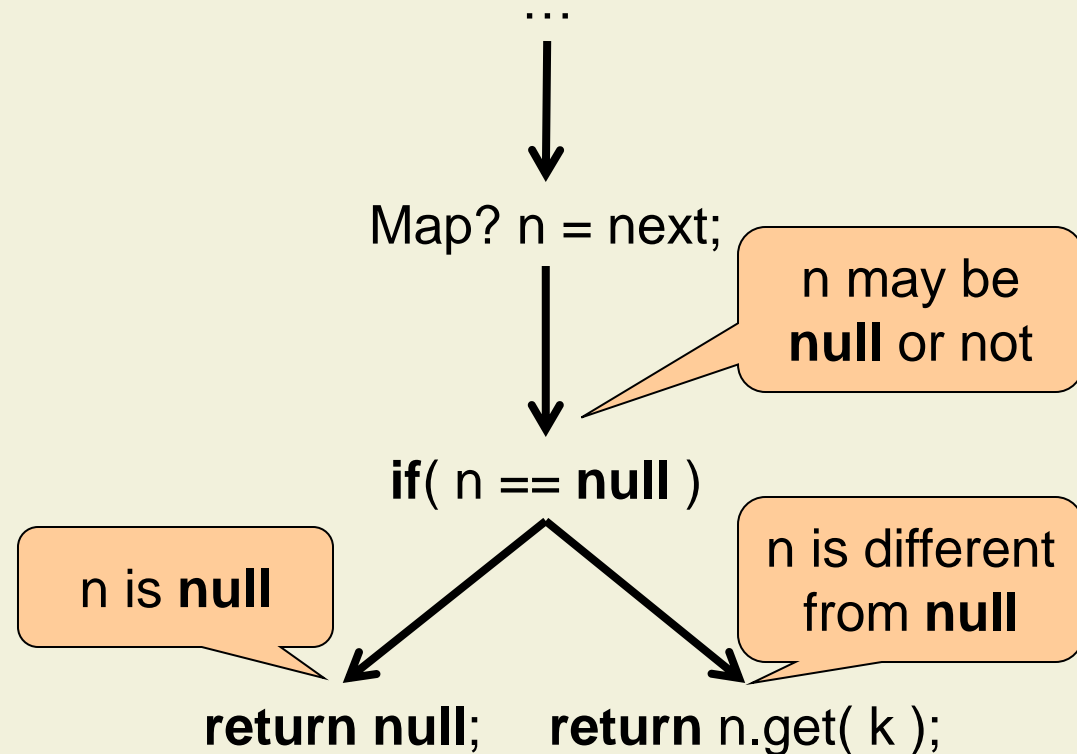
Control Flow Graph



Comparing against null (cont'd)

```
class Map {  
  Map? next;  
  ...  
  Object? get( Object! k ) {  
    ...  
    Map? n = next;  
    if( n == null ) return null;  
    return n.get( k );  
  }  
}
```

Control Flow Graph

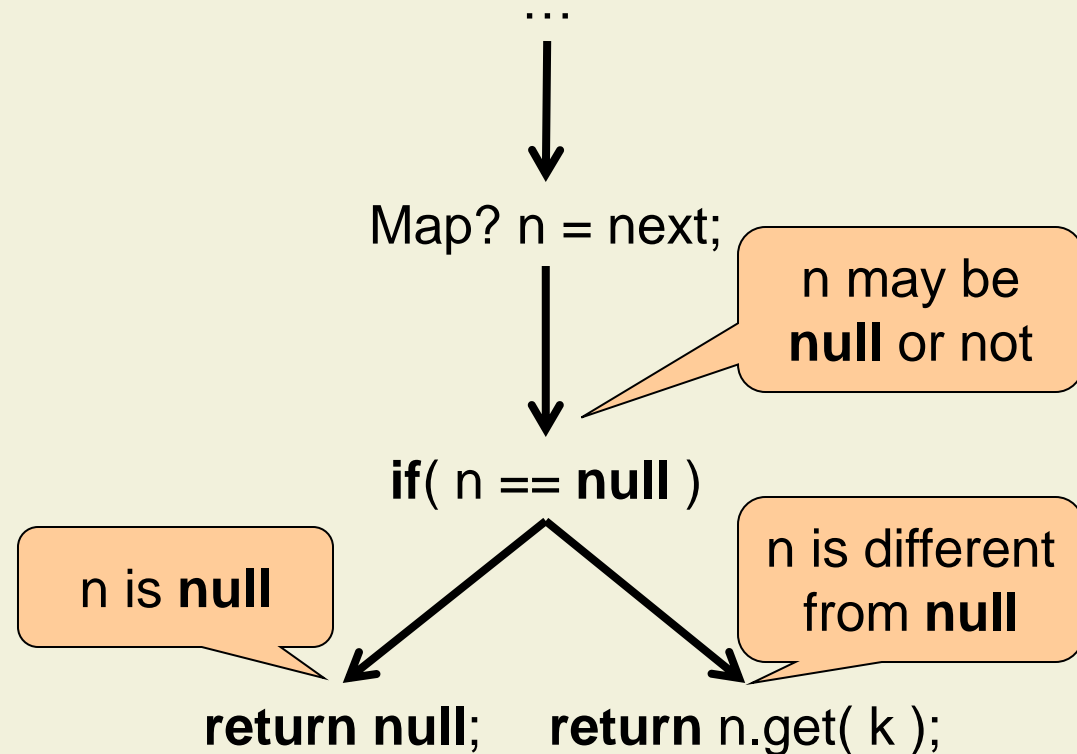


Comparing against null (cont'd)

```
class Map {  
  Map? next;  
  ...  
  Object? get( Object! k ) {  
    ...  
    Map? n = next;  
    if( n == null ) return null;  
    return n.get( k );  
  }  
}
```

Dataflow analysis
guarantees that
this call is safe

Control Flow Graph



Limitations of Data Flow Analysis

```
class Map {  
  Map? next;  
  ...  
  Object? get( Object! k ) {  
    ...  
    Map? n = next;  
    if( n == null ) return null;  
    return n.get( k );  
  }  
}
```

```
class Map {  
  Map? next;  
  ...  
  Object? get( Object! k ) {  
    ...  
    if( next == null ) return null;  
    return next.get( k );  
  }  
}
```

Limitations of Data Flow Analysis

```
class Map {  
    Map? next;  
    ...  
    Object? get( Object! k ) {  
        ...  
        Map? n = next;  
        if( n == null ) return null;  
        return n.get( k );  
    }  
}
```

```
class Map {  
    Map? next;  
    ...  
    Object? get( Object! k ) {  
        ...  
        if( next == null ) return null;  
        return next.get( k );  
    }  
}
```

Limitations of Data Flow Analysis (cont'd)

```
class Map {  
    Map? next;  
    ...  
    Object? get( Object! k ) {  
        ...  
        if( next == null ) return null;  
        someObject.foo( this );  
        return next.get( k );  
    }  
}
```

```
void foo( Map! m ) {  
    m.next = null;  
}
```

- Receiver expression **must not access heap locations**
- Data flow analysis tracks values of local variables, but not heap locations
 - Tracking heap locations is in general non-modular
- In concurrent programs, **other threads** could modify heap locations

8. Initialization

8.1 Simple Non-Null Types

8.2 Object Initialization

8.3 Initialization of Global Data

Constructing New Objects

```
class Map {  
    Map? next;  
    Object! key;  
    Object! value;  
  
    Map( Object! k, Object! v ) {  
        key = k;  
        value = v;  
    }  
}
```


Constructing New Objects

```
class Map {  
    Map? next;  
    Object! key;  
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    Map( Object! k, Object! v ) {  
        key = k;  
        value = v;  
    }  
}
```

All fields are
initialized to **null**

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```

All fields are
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Type invariant is
violated here!

Constructing New Objects

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```

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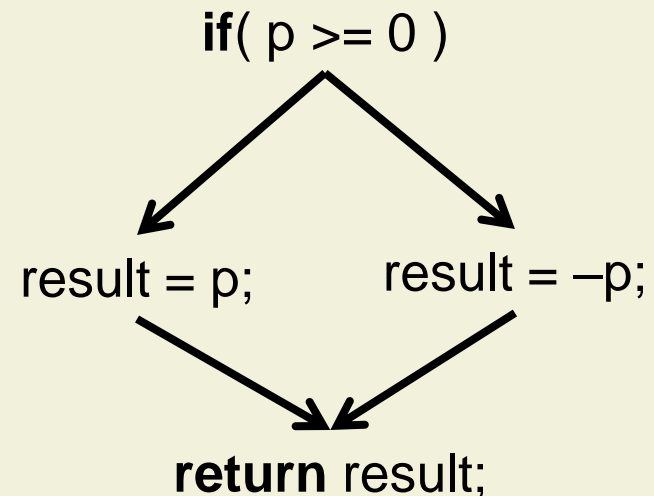
⑩ Idea:

- Make sure all non-null fields are initialized when the constructor terminates
- Do not rely on non-nullness of fields of objects under construction

Definite Assignment of Local Variables

- Java and C# do not initialize local variables
- **Definite assignment rule**: every local variable must be assigned to before it is first used
 - Checked by compiler using a data flow analysis
 - Also checked during bytecode verification

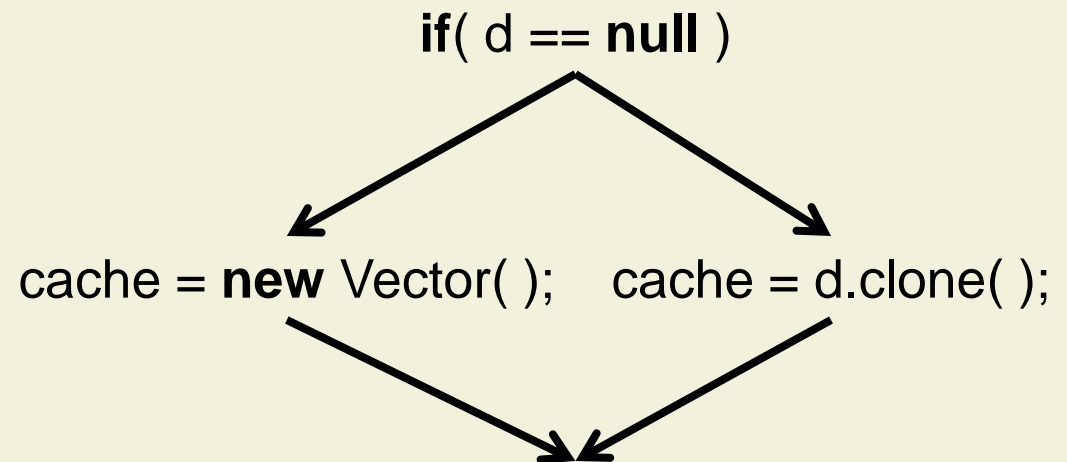
```
int abs( int p ) {  
    int result;  
    if( p >= 0 ) result = p;  
    else result = -p;  
    return result;  
}
```



Definite Assignment of Fields

- Idea: apply definite assignment rule for fields in constructor
 - Eiffel's solution for attached types

```
class Demo {  
  Vector! cache;  
  Demo( Vector? d ) {  
    if( d == null )  
      cache = new Vector( );  
    else  
      cache = d.clone( );  
  }  
}
```



Problem 1: Method Calls

```
class Demo {  
    Vector! cache;  
  
    Demo( ) {  
        int size = optimalSize( );  
        cache = new Vector( size );  
    }  
  
    int optimalSize( ) {  
        return 16;  
    }  
}
```

Problem 1: Method Calls

```
class Demo {  
    Vector! cache;  
  
    Demo( ) {  
        int size = optimalSize( );  
        cache = new Vector( size );  
    }  
  
    int optimalSize( ) {  
        return 16;  
    }  
}
```

```
class Sub extends Demo {  
    Vector! data;  
  
    Sub( Vector! d ) {  
        data = d.clone( );  
    }  
  
    int optimalSize( ) {  
        return data.size( ) * 2;  
    }  
}
```

Problem 1: Method Calls

```
class Demo {  
    Vector! cache;  
  
    Demo( ) {  
        int size = optimalSize( );  
        cache = new Vector( size );  
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    int optimalSize( ) {  
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    }  
}
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class Sub extends Demo {  
    Vector! data;  
  
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        data = d.clone( );  
    }  
  
    int optimalSize( ) {  
        return data.size( ) * 2;  
    }  
}
```

```
Vector! v = new Vector( );  
Sub! s = new Sub( v );
```


Problem 1: Method Calls

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    Vector! cache;  
  
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        int size = optimalSize( );  
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Implicit
super-call

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Vector! v = new Vector( );  
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}
```

Dynamically
bound

```
class Sub extends Demo {  
    Vector! data;  
  
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    }  
  
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        return data.size( ) * 2;  
    }  
}
```

Implicit
super-call

NullPointerException

```
Vector! v = new Vector( );  
Sub! s = new Sub( v );
```

Problem 2: Call-backs

```
class Demo implements Observer {  
    static Subject! subject;  
  
    Demo( ) {  
        subject.register( this );  
    }  
  
    void update( ... ) { }  
}
```

```
class Subject {  
    void register( Observer! o ) {  
        ...  
        o.update( ... );  
    }  
}
```

Problem 2: Call-backs

```
class Demo implements Observer {  
    static Subject! subject;  
  
    Demo( ) {  
        subject.register( this );  
    }  
  
    void update( ... ) { }  
}
```

```
class Sub extends Demo {  
    Vector! data;  
  
    Sub( Vector! d ) { data = d.clone( ); }  
    void update( ... ) { ... data.size( ) ... }  
}
```

```
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```

```
class Sub extends Demo {  
    Vector! data;  
  
    Sub( Vector! d ) { data = d.clone( ); }  
    void update( ... ) { ... data.size( ) ... }  
}
```

```
class Subject {  
    void register( Observer! o ) {  
        ...  
        o.update( ... );  
    }  
}
```

```
Vector! v = new Vector( );  
Sub! s = new Sub( v );
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        o.update( ... );  
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```

Dynamically bound

```
class Sub extends Demo  
    Vector! data;  
  
    Sub( Vector! d ) { data = d.clone( ); }  
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```

Implicit super-call

```
Vector! v = new Vector( );  
Sub! s = new Sub( v );
```

NullPointerException

Problem 3: Escaping via Method Calls

```
class Demo implements Observer {  
    static Subject! subject;  
  
    Demo( ) {  
        subject.register( this );  
    }  
  
    void update( ... ) { }  
}
```

```
class Sub extends Demo {  
    Vector! data;  
  
    Sub( Vector! d ) { data = d.clone( ); }  
    void update( ... ) { ... data.size( ) ... }  
}
```

```
class Subject extends Thread {  
    List<Observer!>! list;  
  
    void register( Observer! o )  
    { list.add( o ); }  
  
    void run( ) {  
        while( true ) {  
            if( sensorValueChanged( ) )  
                for( Observer! o: list )  
                    o.update( ... );  
        }  
    }  
    ...  
}
```

Problem 3: Escaping via Method Calls

```
class Demo implements Observer {  
    static Subject! subject;  
  
    Demo( ) {  
        subject.register( this );  
    }  
  
    void update( ... ) { }  
}
```

```
class Sub extends Demo {  
    Vector! data;  
  
    Sub( Vector! d ) { data = d.clone( ); }  
    void update( ... ) { ... data.size( ) ... }  
}
```

```
class Subject extends Thread {  
    List<Observer!>! list;  
  
    void register( Observer! o )  
    { list.add( o ); }  
  
    void run( ) {  
        while( true ) {  
            if( sensorValueChanged( ) )  
                for( Observer! o: list )  
                    o.update( ... );  
        }  
    }  
    ...  
}
```

No call-
back

Problem 3: Escaping via Method Calls

```
class Demo implements Observer {  
    static Subject! subject;  
  
    Demo( ) {  
        subject.register( this );  
    }  
  
    void update( ... ) { }  
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```
class Sub extends Demo {  
    Vector! data;  
  
    Sub( Vector! d ) { data = d.clone( ); }  
    void update( ... ) { ... data.size( ) ... }  
}
```

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class Subject extends Thread {  
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    { list.add( o ); }  
  
    void run( ) {  
        while( true ) {  
            if( sensorValueChanged( ) )  
                for( Observer! o: list )  
                    o.update( ... );  
        }  
    }  
    ...  
}
```

No call-back

Call may occur at any time

Problem 3: Escaping via Method Calls

```
class Demo implements Observer {  
    static Subject! subject;  
  
    Demo( ) {  
        subject.register( this );  
    }  
  
    void update( ... ) { }  
}
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```
class Sub extends Demo {  
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}
```

NullPointerException

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            if( sensorValueChanged( ) )  
                for( Observer! o: list )  
                    o.update( ... );  
        }  
    }  
    ...  
}
```

No call-back

Call may occur at any time

Problem 4: Escaping via Field Updates

```
class Node {  
    Node! next; // a cyclic list  
    Process! proc;  
  
    Node( Node! after, Process! p ) {  
        this.next = after.next;  
        after.next = this;  
        proc = p;  
    }  
}
```

```
class Scheduler extends Thread {  
    Node! current;  
  
    void run( ) {  
        while( true ) {  
            current.proc.preempt( );  
            current = current.next;  
            current.proc.resume( );  
            Thread.sleep( 1000 );  
        }  
    }  
    ...  
}
```

Problem 4: Escaping via Field Updates

```
class Node {  
    Node! next; // a cyclic list  
    Process! proc;  
  
    Node( Node! after, Process! p ) {  
        this.next = after.next;  
        after.next = this;  
        proc = p;  
    }  
}
```

Assume scheduler
runs now, with
current == after

```
class Scheduler extends Thread {  
    Node! current;  
  
    void run( ) {  
        while( true ) {  
            current.proc.preempt( );  
            current = current.next;  
            current.proc.resume( );  
            Thread.sleep( 1000 );  
        }  
    }  
    ...  
}
```

Problem 4: Escaping via Field Updates

```
class Node {  
    Node! next; // a cyclic list  
    Process! proc;  
  
    Node( Node! after, Process! p ) {  
        this.next = after.next;  
        after.next = this;  
        proc = p;  
    }  
}
```

Assume scheduler
runs now, with
current == after

```
class Scheduler extends Thread {  
    Node! current;  
  
    void run( ) {  
        while( true ) {  
            current.proc.preempt( );  
            current = current.next;  
            current.proc.resume( );  
            Thread.sleep( 1000 );  
        }  
    }  
    ...  
}
```

NullPointerException

Definite Assignment of Fields: Summary

- The simple definite assignment checks for fields are sound only if **partly-initialized objects do not escape** from their constructor
 - Not passed as receiver or argument to a method call
 - Not stored in a field or an array

Definite Assignment of Fields: Summary

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 - Not stored in a field or an array

```
class Node {  
    Node! next;  // a cyclic list  
    String! label;  
  
    Node( String! l ) {  
        this.next = this;  
        this.setLabel( l );  
    }  
  
    void setLabel( String! l ) {  
        this.label = l;  
    }  
}
```

Definite Assignment of Fields: Summary

- The simple definite assignment checks for fields are sound only if **partly-initialized objects do not escape** from their constructor
 - Not passed as receiver or argument to a method call
 - Not stored in a field or an array

```
class Node {  
    Node! next; // a  
    String! label;  
  
    Node( String! l ) {  
        this.next = this;  
        this.setLabel( l );  
    }  
  
    void setLabel( String! l ) {  
        this.label = l;  
    }  
}
```

Field update is safe:
object does not
escape

Definite Assignment of Fields: Summary

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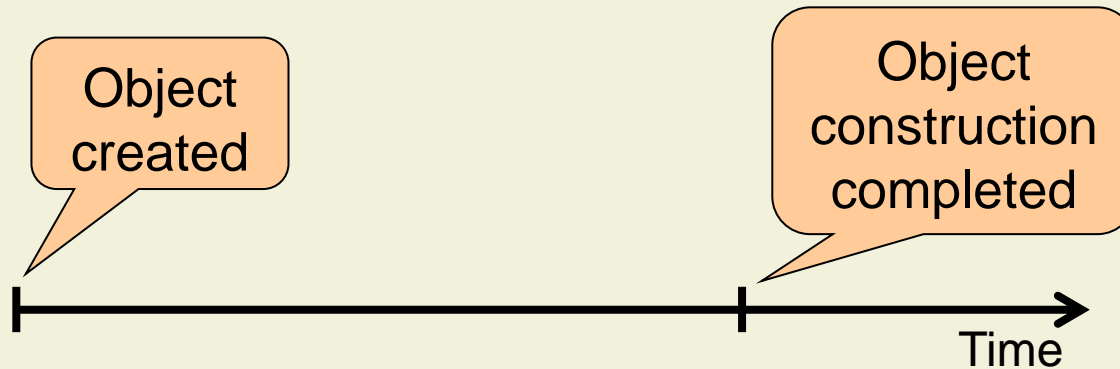
```
class Node {  
    Node! next; // a  
    String! label;  
  
    Node( String! l ) {  
        this.next = this;  
        this.setLabel( l );  
    }  
  
    void setLabel( String! l ) {  
        this.label = l;  
    }  
}
```

Field update is safe:
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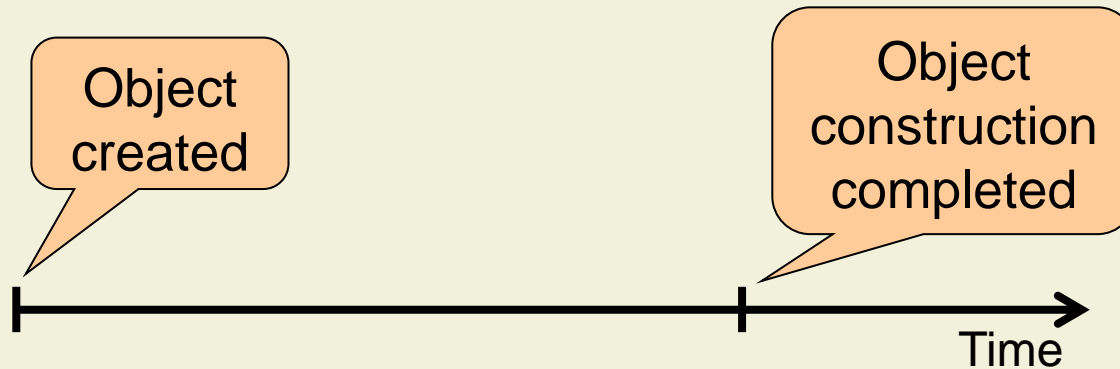
Method call is safe:
no reading of fields
of new object

Initialization Phases

Initialization Phases

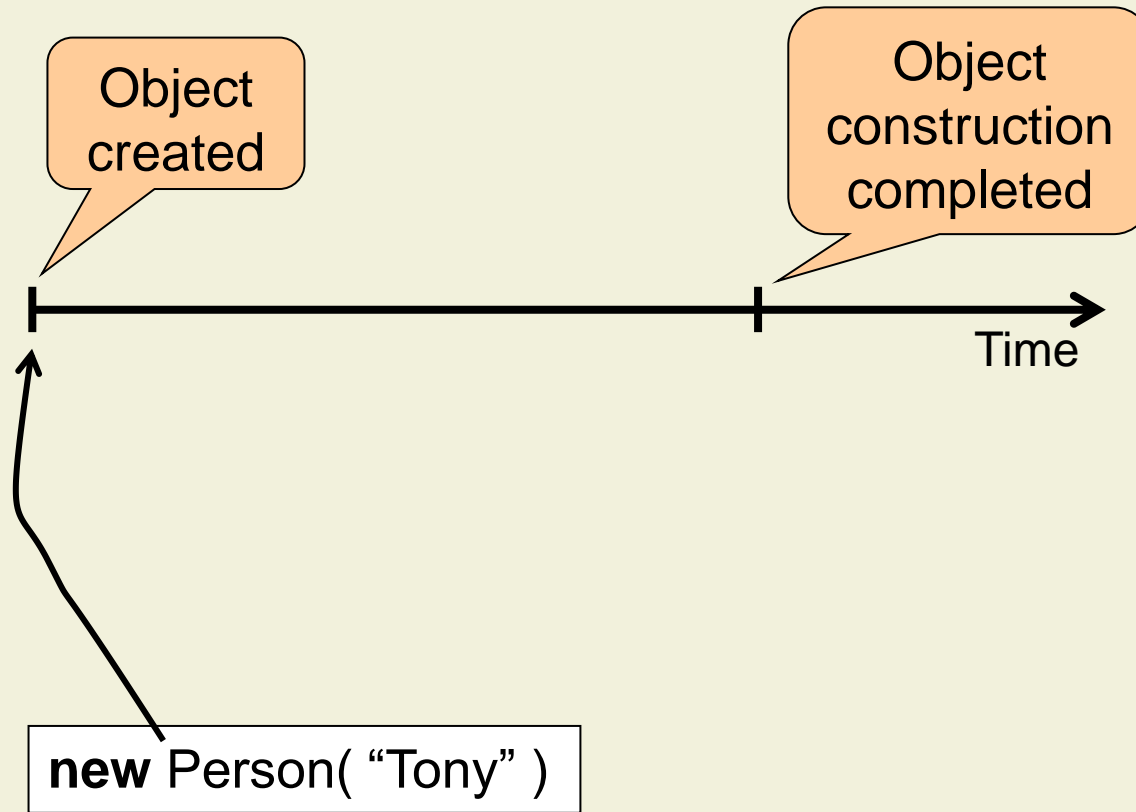


Initialization Phases

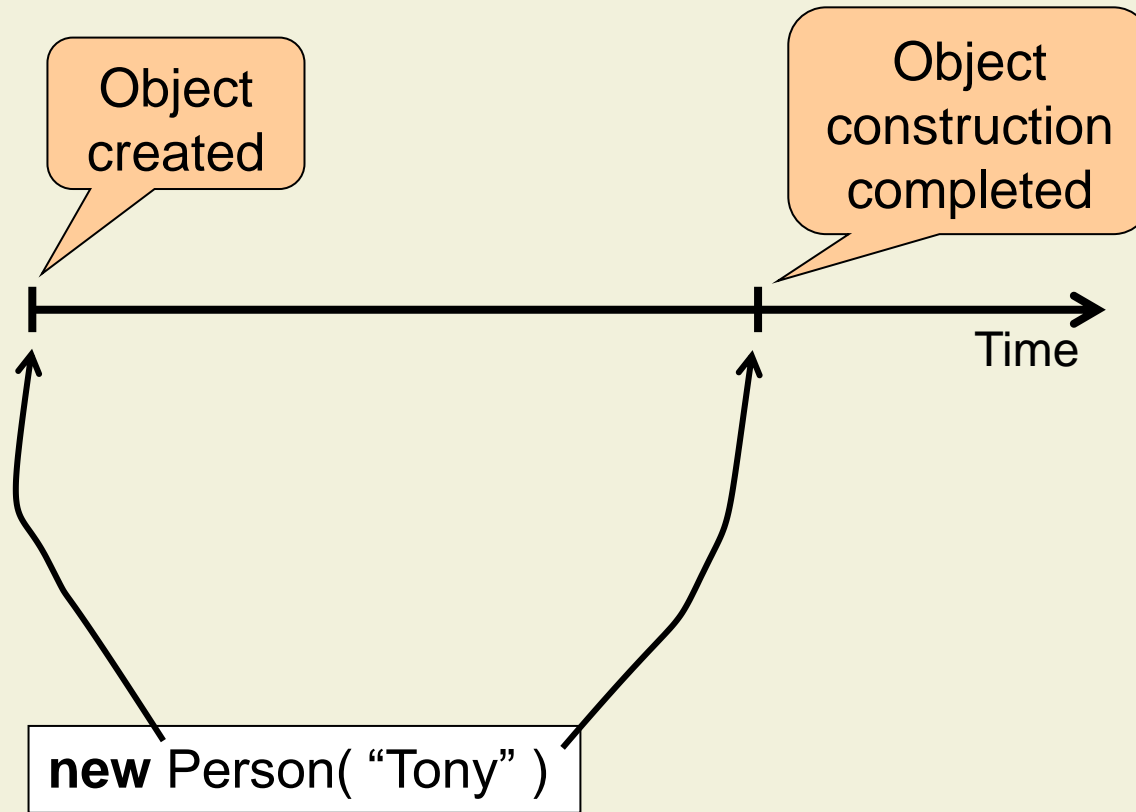


```
new Person( "Tony" )
```

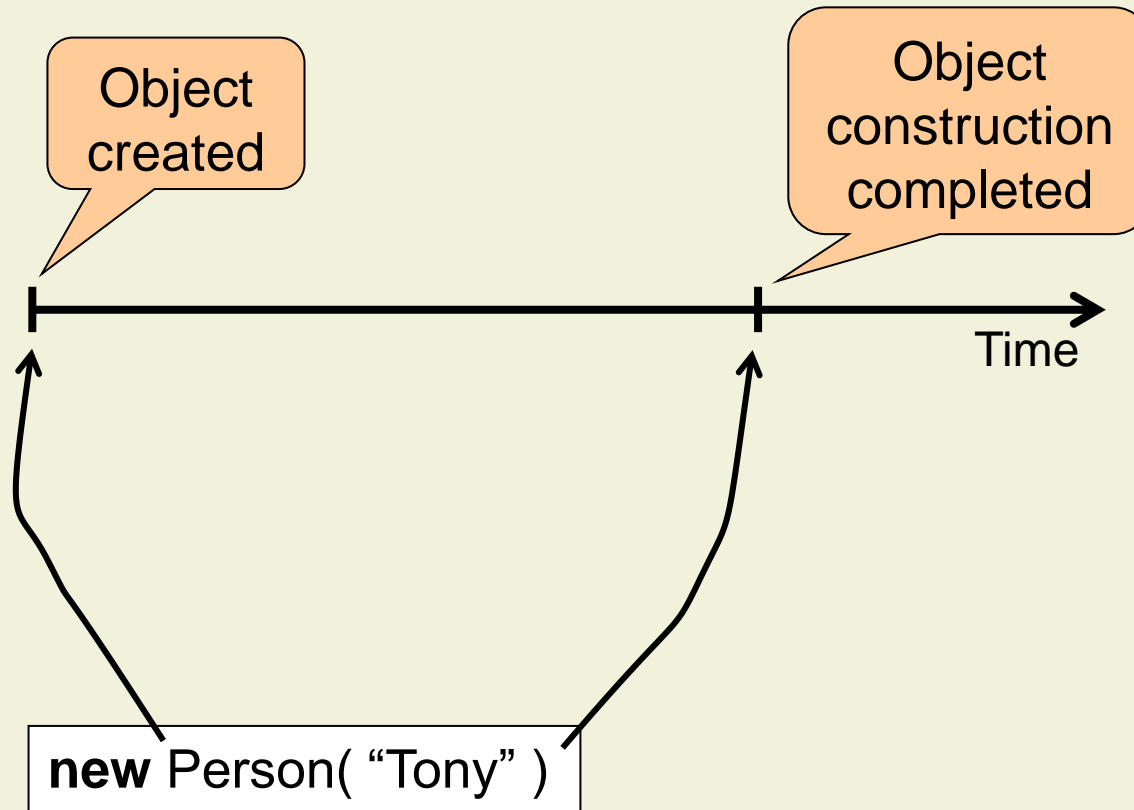
Initialization Phases



Initialization Phases

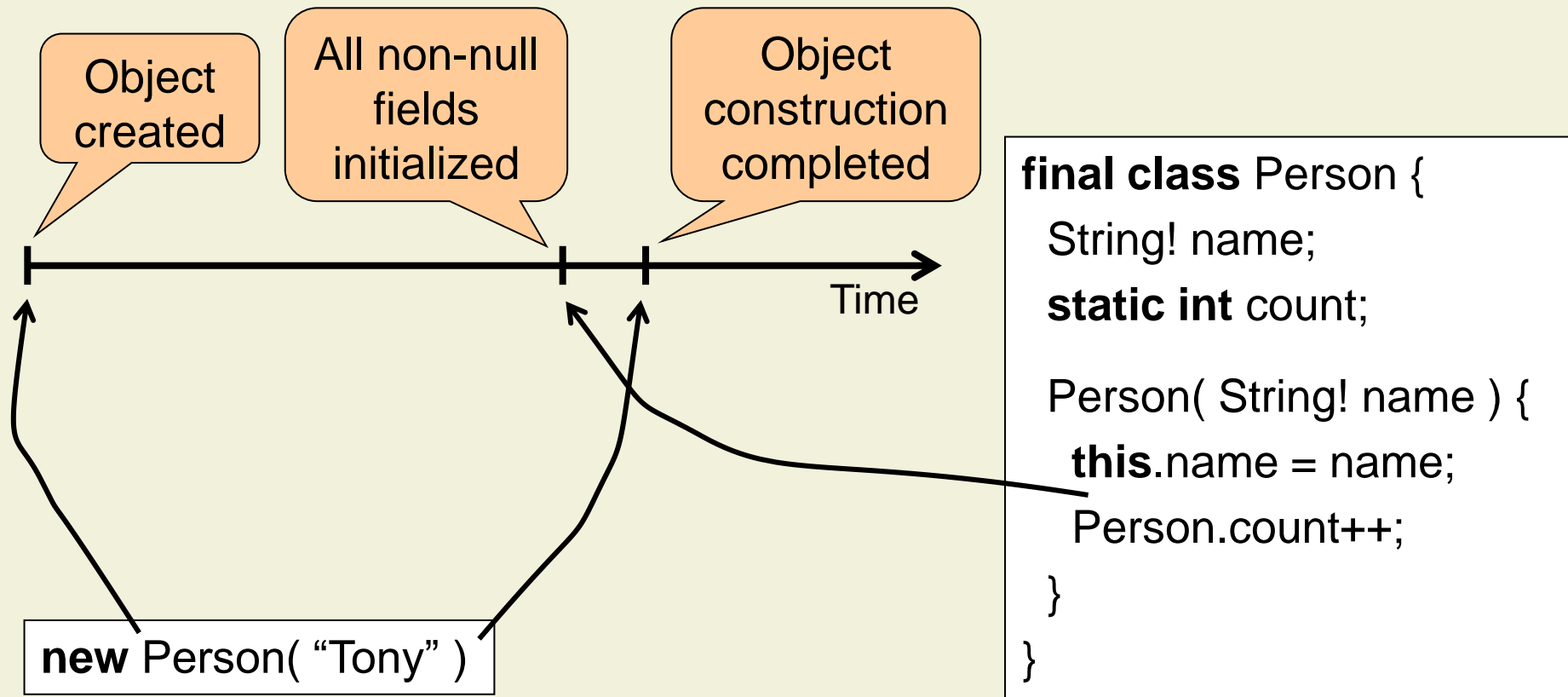


Initialization Phases

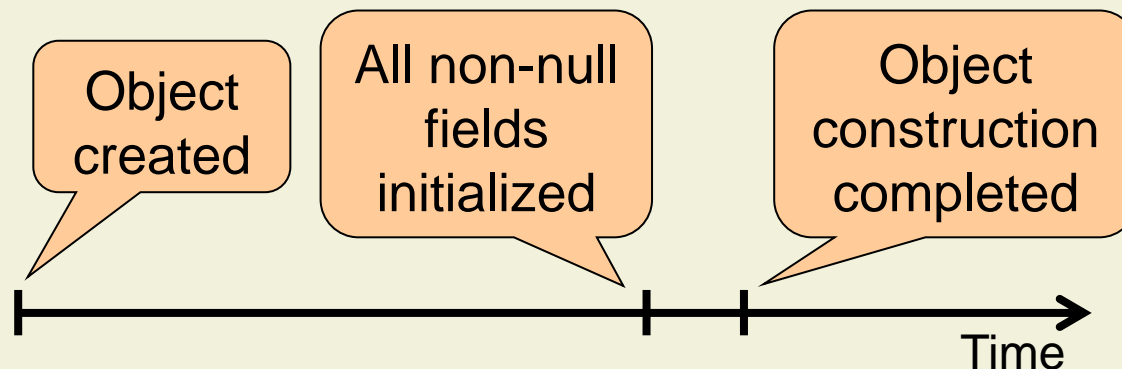


```
final class Person {  
    String! name;  
    static int count;  
  
    Person( String! name ) {  
        this.name = name;  
        Person.count++;  
    }  
}
```

Initialization Phases

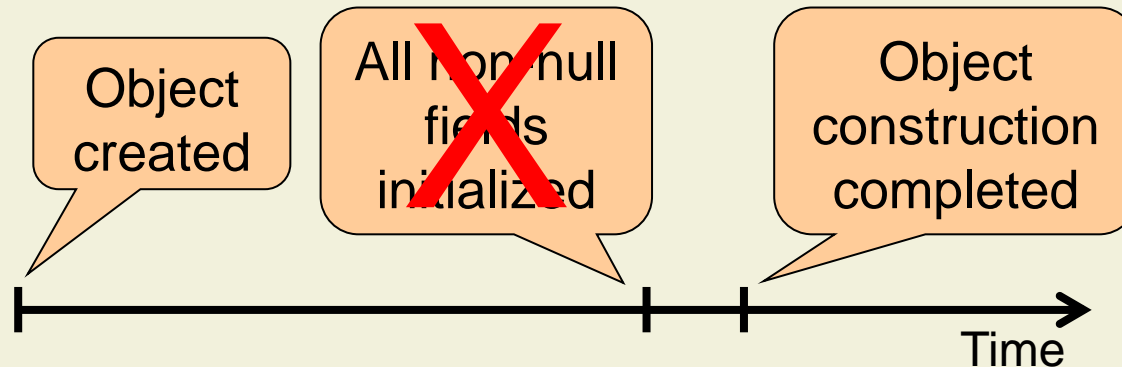


Tracking Object Construction



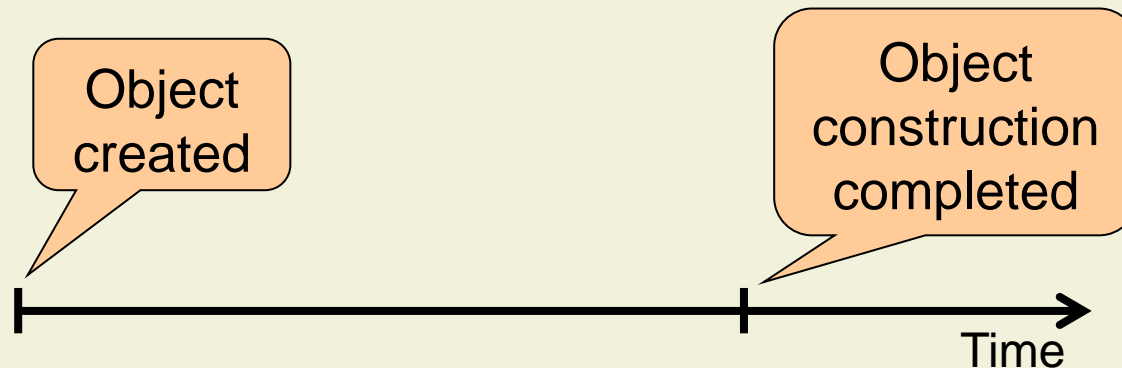
- Idea: design a type system that tracks **which objects are under construction**
 - For simplicity, we track whether the construction has completed (non-null fields may be initialized earlier)
- (Simplified) type invariant:
If the static type of an expression e is a non-null type then e 's value at run time is different from **null**

Tracking Object Construction



- Idea: design a type system that tracks **which objects are under construction**
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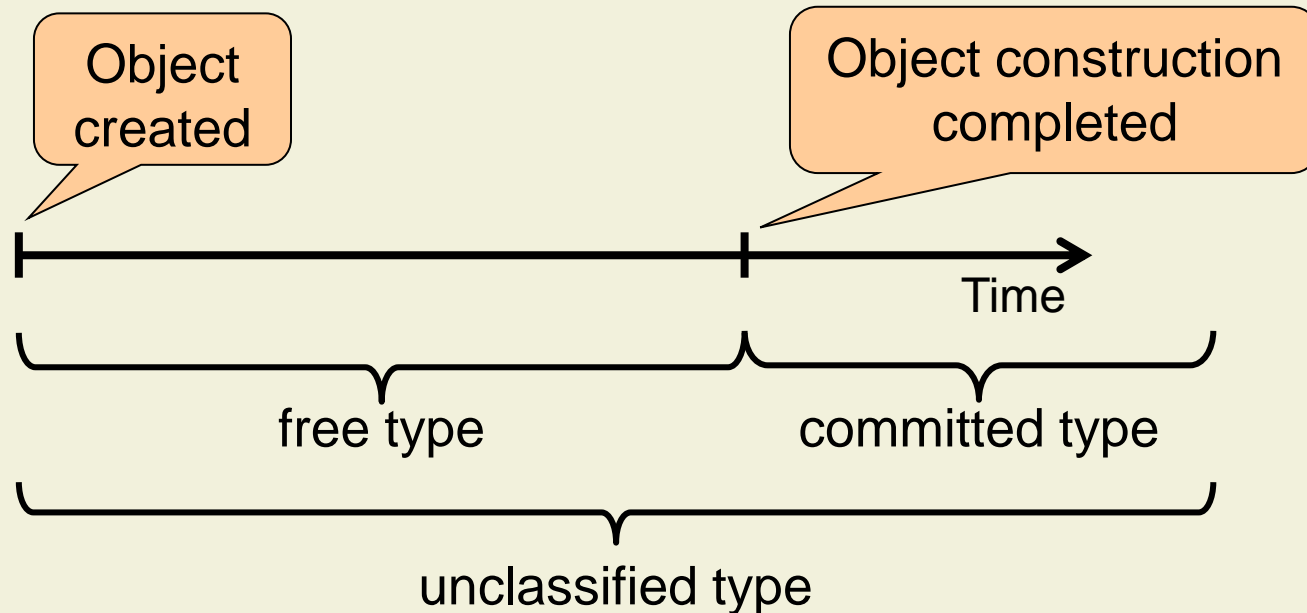
Tracking Object Construction



- Idea: design a type system that tracks **which objects are under construction**
 - For simplicity, we track whether the construction has completed (non-null fields may be initialized earlier)
- (Simplified) type invariant:
If the static type of an expression e is a non-null type then e 's value at run time is different from **null**

Construction Types

- For every class or interface T , we introduce **different types** for references:
 - to objects under construction
 - to objects whose construction is completed



Construction Types: Details

- For a class or interface T , we introduce six types
 - $T!$ and $T?$ (committed types)
 - **free** $T!$ and **free** $T?$ (free types)
 - **unc** $T!$ and **unc** $T?$ (unclassified types)
- Subtyping
 - $T!$ and **free** $T!$ are subtypes of **unc** $T!$
 - $T?$ and **free** $T?$ are subtypes of **unc** $T?$
 - No casts from unclassified to free or committed types

$T! \text{ c}T = \dots$
free $T! \text{ f}T = \dots$
unc $T? \text{ u}T = \dots$

$\text{u}T = \text{c}T;$
 $\text{u}T = \text{f}T;$
unc $T! \text{ n}T = (\text{unc } T!) \text{ u}T;$

$\text{f}T = \text{c}T;$
 $\text{c}T = (T!) \text{ u}T;$
 $\text{f}T = (\text{free } T!) \text{ u}T;$

Requirement 1: Local Initialization

- An object is **locally initialized** if its **non-null fields have non-null values**
- If the static type of an expression e is a **committed** type then e 's value at run time is **locally initialized**
- Non-null type of a field read $e.f$

		non-null type of f	
construction type of e		!	?
	committed	!	?
	free	?	?
	unc	?	?

Heap Traversal

```
class Node {  
    Node! next; // a cyclic list  
    Object? elem;  
  
    boolean contains( Object? e ) {  
        _____ Node! ptr = this.next;  
        while( ptr != this ) {  
            if( ptr.elem.equals( e ) )  
                return true;  
            ptr = ptr.next;  
        }  
        return false;  
    }  
}
```

Heap Traversal

```
class Node {  
    Node! next; // a cyclic list  
    Object? elem;  
  
    boolean contains( Object? e ) {  
        _____ Node! ptr = this.next;  
        while( ptr != this ) {  
            if( ptr.elem.equals( e ) )  
                return true;  
            ptr = ptr.next;  
        }  
        return false;  
    }  
}
```

Heap Traversal

```
class Node {  
    Node! next; // a cyclic list  
    Object? elem;  
  
    boolean contains( Object? e ) {  
        committed Node! ptr = this.next;  
        while( ptr != this ) {  
            if( ptr.elem.equals( e ) )  
                return true;  
            ptr = ptr.next;  
        }  
        return false;  
    }  
}
```

ptr has to be
committed

Requirement 2: Transitive Initialization

- An object is **transitively initialized** if **all reachable objects are locally initialized**
- If the static type of an expression e is a **committed** type then e 's value at run time is **transitively initialized**

Requirement 3: Cyclic Structures

```
class Node {  
    Node! next; // a cyclic list  
    String! id;  
  
    Node( String! s ) {  
        this.next = this;  
        this.id = s;  
    }  
}
```

Requirement 3: Cyclic Structures

```
class Node {  
  Node! next; // a cyclic list  
  String! id;  
  
  Node( String! s ) {  
    this.next = this;  
    this.id = s;  
  }  
}
```

this is free
inside
constructor

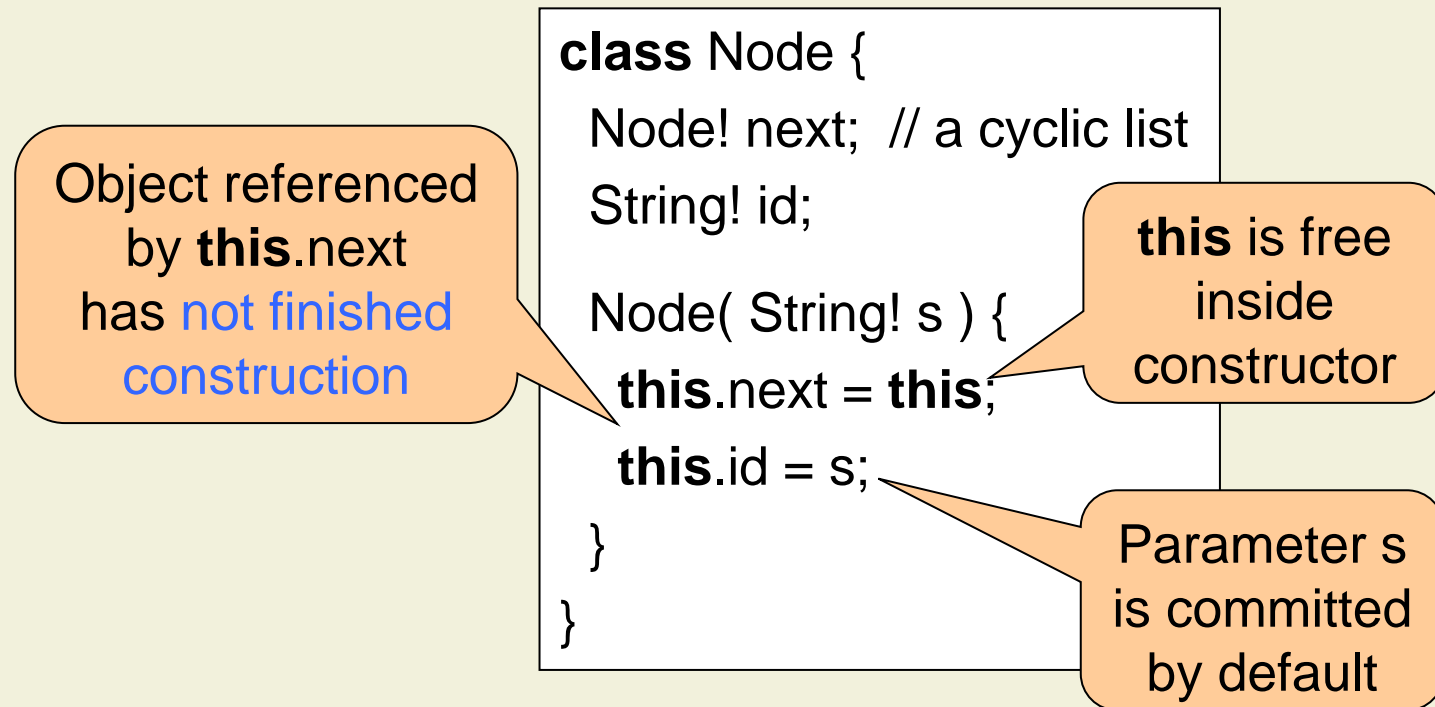
Requirement 3: Cyclic Structures

Object referenced
by **this.next**
has **not finished**
construction

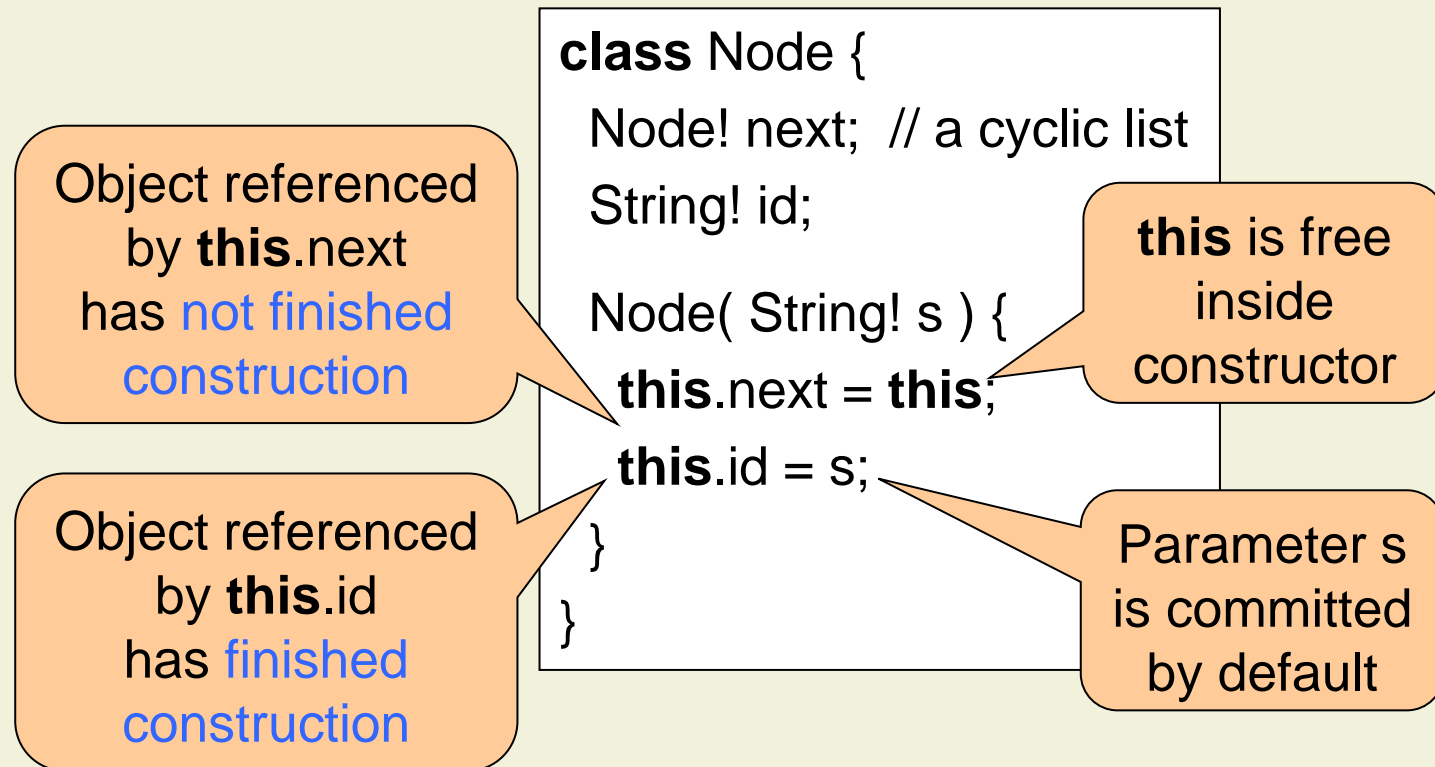
```
class Node {  
  Node! next; // a cyclic list  
  String! id;  
  
  Node( String! s ) {  
    this.next = this;  
    this.id = s;  
  }  
}
```

this is free
inside
constructor

Requirement 3: Cyclic Structures



Requirement 3: Cyclic Structures



Type Rules: Field Write

- A field write $e_1.f = e_2$ is well-typed if
 - e_1 and e_2 are well-typed
 - e_1 's type is a non-null type
 - e_2 's class and non-null type conform to the type of $e_1.f$
 - e_1 's type is free or e_2 's type is committed

		Type of e_2		
		committed	free	unc
Type of e_1	committed	✓	✗	✗
	free	✓	✓	✓
	unc	✓	✗	✗

Type Rules: Field Read

- A field read expression $e.f$ is well-typed if
 - e is well-typed
 - e 's type is a non-null type
- The type of $e.f$ is

		Declared type of f	
		$T!$	$T?$
Type of e	$S!$	$T!$	$T?$
	free $S!$	unc $T?$	unc $T?$
	unc $S!$	unc $T?$	unc $T?$

Type Rules: Constructors

- Constructor signatures include construction types for all parameters
 - Receiver has free, non-null type

```
class Node {  
  Node! next;  // cyclic list  
  String! id;  
  
  Node( String! name ) {  
    next = this;  
    id = this.getId( name );  
  }  
}
```

Type Rules: Constructors

- Constructor signatures include construction types for all parameters
 - Receiver has free, non-null type

this is of a free type

```
class Node {  
  Node! next;  // cyclic list  
  String! id;  
  
  Node( String! name ) {  
    next = this;  
    id = this.getId( name );  
  }  
}
```

Type Rules: Constructors

- Constructor signatures include construction types for all parameters
 - Receiver has free, non-null type

this is of a free type

```
class Node
Node! next
String! id;
Node( String! name ) {
    next = this;
    id = this.getId( name );
}
```

name is of a committed type

Type Rules: Constructors

- Constructor signatures include construction types for all parameters
 - Receiver has free, non-null type

this is of a free type

```
class Node
  Node! next
  String! id;
  Node( String! name ) {
    next = this;
    id = this.get...
  }
}
```

name is of a committed type

Non-nullness invariant is satisfied

Type Rules: Constructors

- Constructor signatures include construction types for all parameters
 - Receiver has free, non-null type
- Constructor bodies must assign non-null values to all non-null fields of the receiver

```
class Node {  
    Node! next;  // cyclic list  
    String! id;  
  
    Node( String! name ) {  
        next = this;  
        id = this.getId( name );  
    }  
}
```

Type Rules: Constructors

- Constructor signatures include construction types for all parameters
 - Receiver has free, non-null type
- Constructor bodies must assign non-null values to all non-null fields of the receiver

```
class Node {  
  Node! next;  // cyclic list  
  String! id;  
  
  Node( String! name ) {  
    next = this;  
    id = this.getId( name );  
  }  
}
```

Definite
assignment
check succeeds

Type Rules: Methods and Calls

- Method signatures include construction types for all parameters

```
class Node {  
  Node! next;  // cyclic list  
  String! id;  
  
  Node( String! name ) {  
    next = this;  
    id = this.getId( name );  
  }  
  
  String! free getId( String! n )  
  { return ...; }  
}
```

Type Rules: Methods and Calls

- Method signatures include construction types for all parameters

```
class Node {  
  Node! next;  // cyclic list  
  String! id;  
  
  Node( String! name ) {  
    next = this;  
    id = this.getId( name );  
  }  
  
  String! free getId( String! n )  
  { return ...; }
```

this is of a
free type

Type Rules: Methods and Calls

- Method signatures include construction types for all parameters
- Calls are type-checked as usual

```
class Node {  
  Node! next;  // cyclic list  
  String! id;  
  
  Node( String! name ) {  
    next = this;  
    id = this.getId( name );  
  }  
  
  String! free getId( String! n )  
  { return ...; }
```

this is of a
free type

Type Rules: Methods and Calls

- Method signatures include construction types for all parameters
- Calls are type-checked as usual

```
class Node {  
  Node! next; // cyclic list  
  String! id;  
  Node( String!  
    next = this;  
    id = this.getId( name );  
}  
  
String! free getId( String! n )  
{ return ...; }
```

Call is
permitted

this is of a
free type

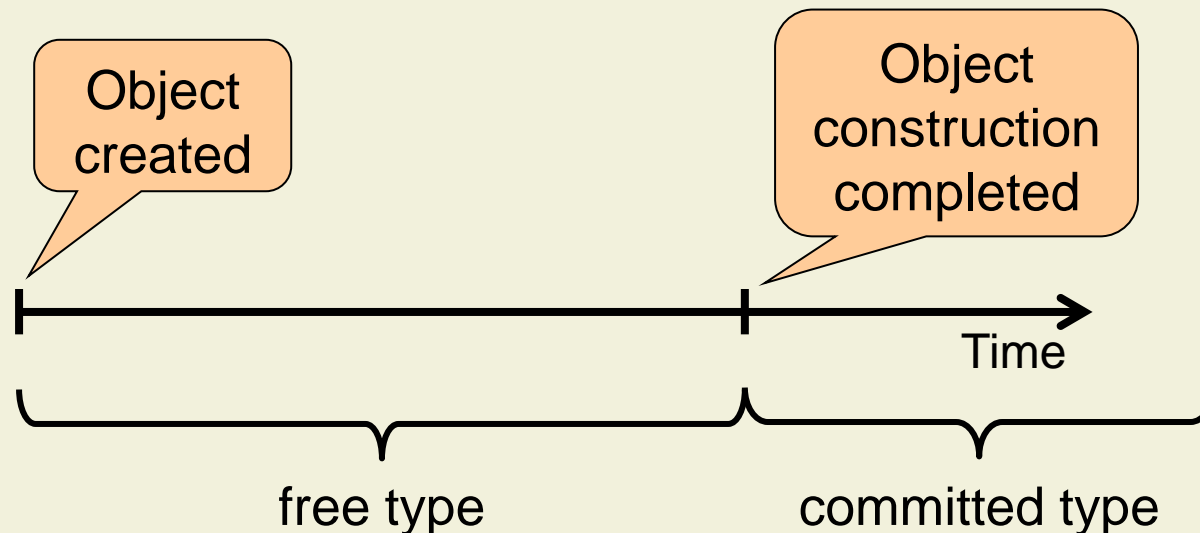
Type Rules: Methods and Calls

- Method signatures include construction types for all parameters
- Calls are type-checked as usual
- Overriding requires the usual co- and contravariance

```
class Node {  
  Node! next;  // cyclic list  
  String! id;  
  
  Node( String! name ) {  
    next = this;  
    id = this.getId( name );  
  }  
  
  String! free getId( String! n )  
  { return ...; }  
}
```

Object Construction

- We have not yet defined **when** the construction of a new object completes



Object Construction (cont'd)

- Is construction finished when the constructor terminates?

```
class Demo {  
    String! name;  
    Demo( ) {  
        name = "Tony";  
    }  
}
```

Object Construction (cont'd)

- Is construction finished when the constructor terminates?

```
class Demo {  
    String! name;  
    Demo( ) {  
        name = "Tony";  
    }  
}
```

```
class Sub extends Demo {  
    Vector! data;  
  
    Sub( ) {  
        data = new Vector( );  
    }  
}
```

Object Construction (cont'd)

- Is construction finished when the constructor terminates?
- Not if there are subclass constructors, which have not yet executed
 - In general not known modularly

```
class Demo {  
    String! name;  
    Demo( ) {  
        name = "Tony";  
    }  
}
```

this is **not**
completely
constructed

```
class Sub extends Demo {  
    Vector! data;  
  
    Sub( ) {  
        data = new Vector( );  
    }  
}
```

Object Construction (cont'd)

- Is construction finished when the **new**-expression terminates?

Object Construction (cont'd)

- Is construction finished when the **new**-expression terminates?

```
class Demo {  
    C! myC;  
    Demo( ) {  
        C! c = new C( this );  
        c.foo( );  
        myC = c;  
    }  
}
```

Object Construction (cont'd)

- Is construction finished when the **new**-expression terminates?

```
class Demo {  
    C! myC;  
    Demo( ) {  
        C! c = new C( this );  
        c.foo( );  
        myC = c;  
    }  
}
```

```
class C {  
    Demo! demo;  
    C( free Demo! d ) { demo = d; }  
    String! foo( ) { return demo.myC.toString( ); }  
}
```

Object Construction (cont'd)

- Is construction finished when the **new**-expression terminates?

```
class Demo {  
  C! myC;  
  Demo( ) {  
    C! c = new C( this );  
    c.foo( );  
    myC = c;  
  }  
}
```

c is locally, but
not transitively
initialized

```
class C {  
  Demo! demo;  
  C( free Demo! d ) { demo = d; }  
  String! foo( ) { return demo.myC.toString( ); }  
}
```

Object Construction (cont'd)

- Is construction finished when the **new**-expression terminates?

```
class Demo {  
    C! myC;  
    Demo( ) {  
        C! c = new C( this );  
        c.foo( );  
        myC = c;  
    }  
}
```

c is locally, but
not transitively
initialized

```
class C {  
    Demo! demo;  
    C( free Demo! d ) { demo = d; }  
    String! foo( ) { return demo.myC.toString( ); }  
}
```

NullPointerException

Object Construction (cont'd)

- Is construction finished when the **new**-expression terminates?
- Not if constructor initializes fields with free references

```
class Demo {  
  C! myC;  
  Demo() {  
    C! c = new C( this );  
    c.foo();  
    myC = c;  
  }  
}
```

c is locally, but
not transitively
initialized

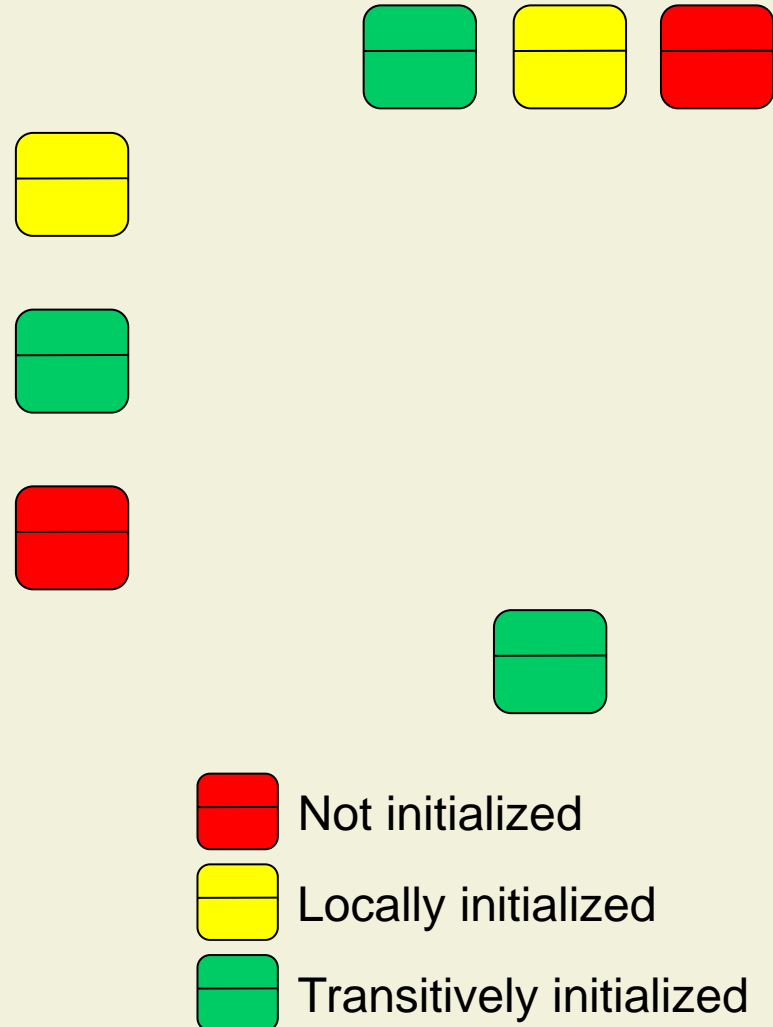
```
class C {  
  Demo! demo;  
  C( free Demo! d ) { demo = d; }  
  String! foo( ) { return demo.myC.toString( ); }  
}
```

NullPointerException

Object Construction

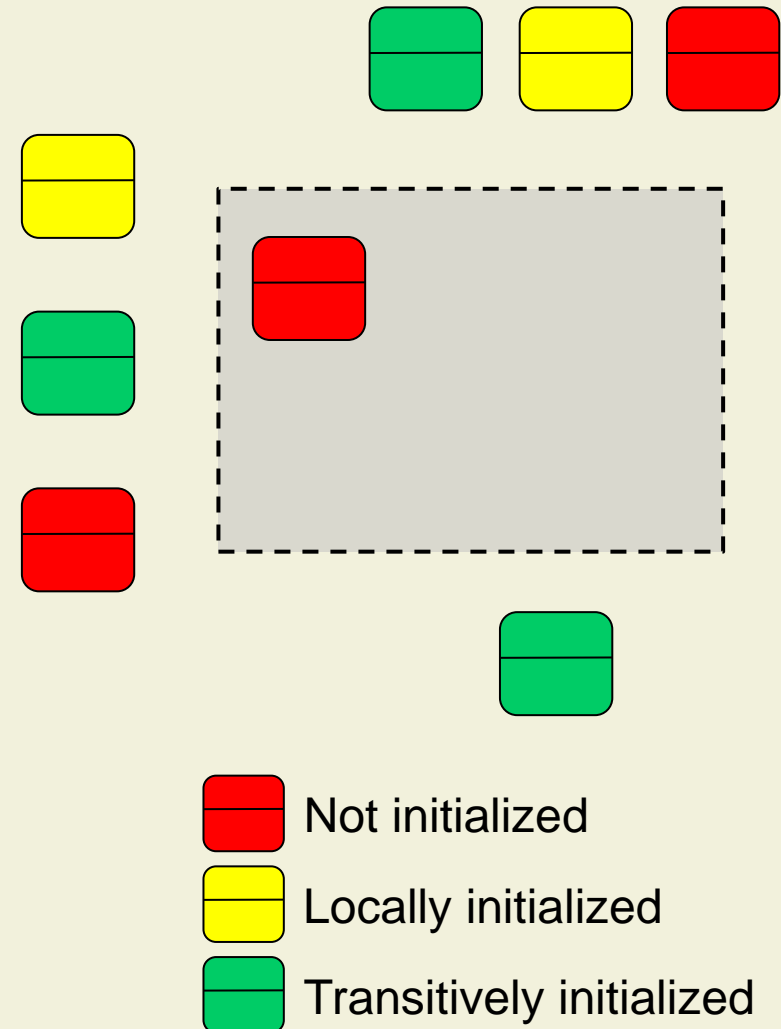
■ Assumptions

- new-expression takes **only committed arguments**
- Nested new-expressions take **arbitrary arguments**



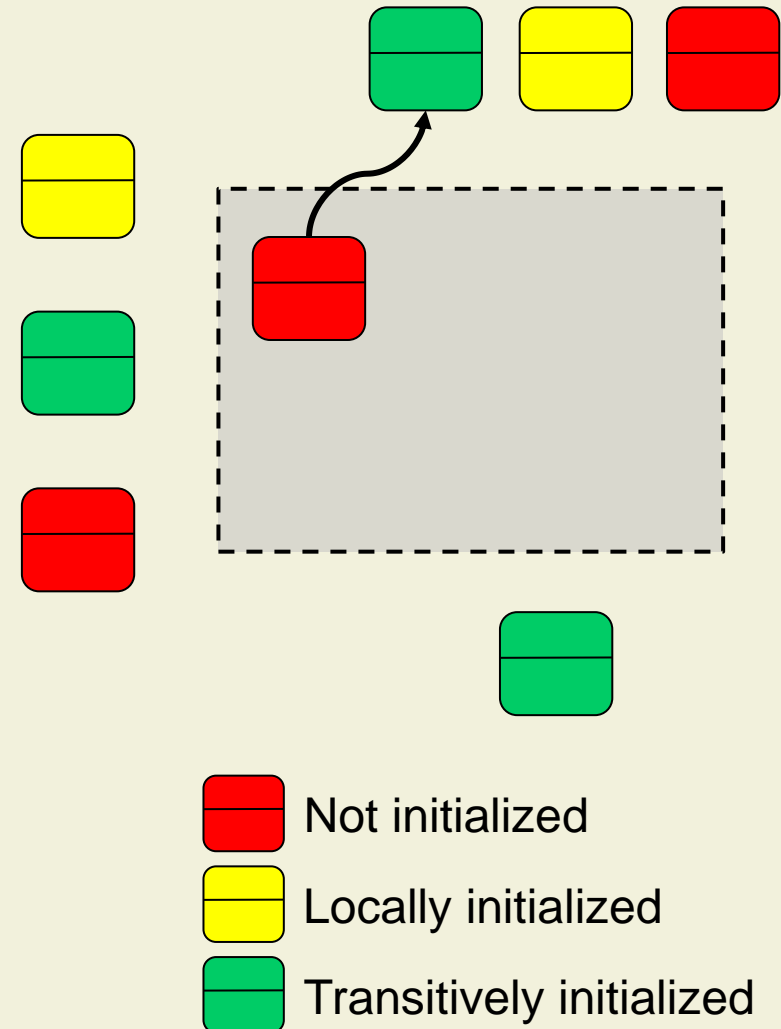
Object Construction

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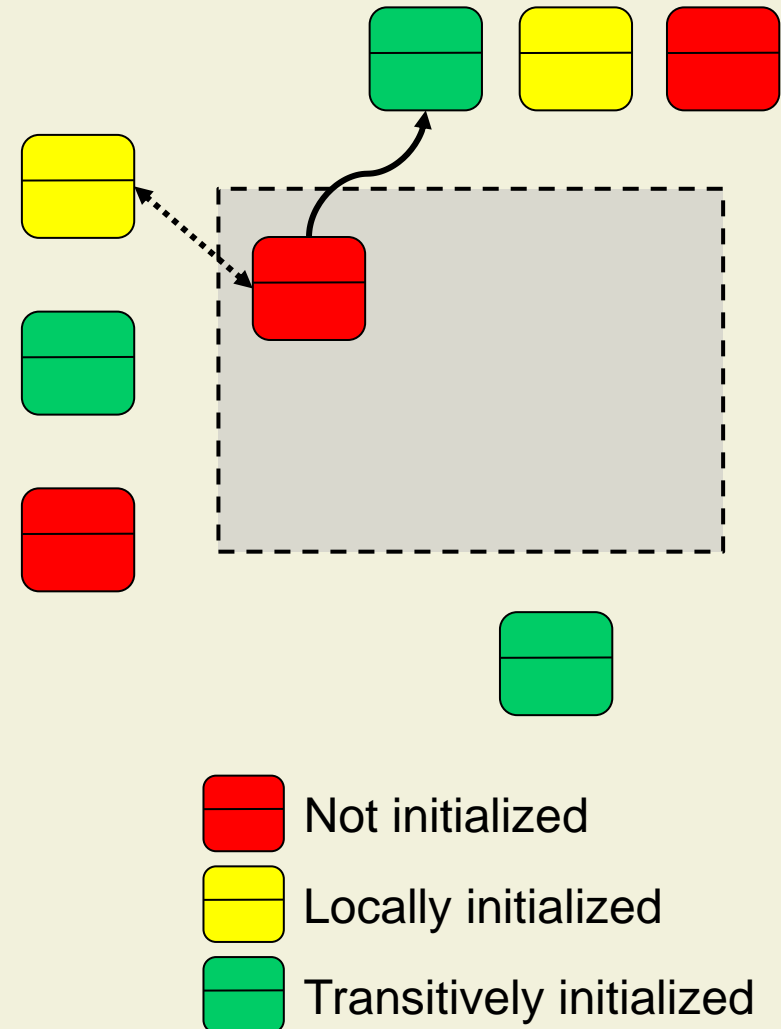
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Object Construction

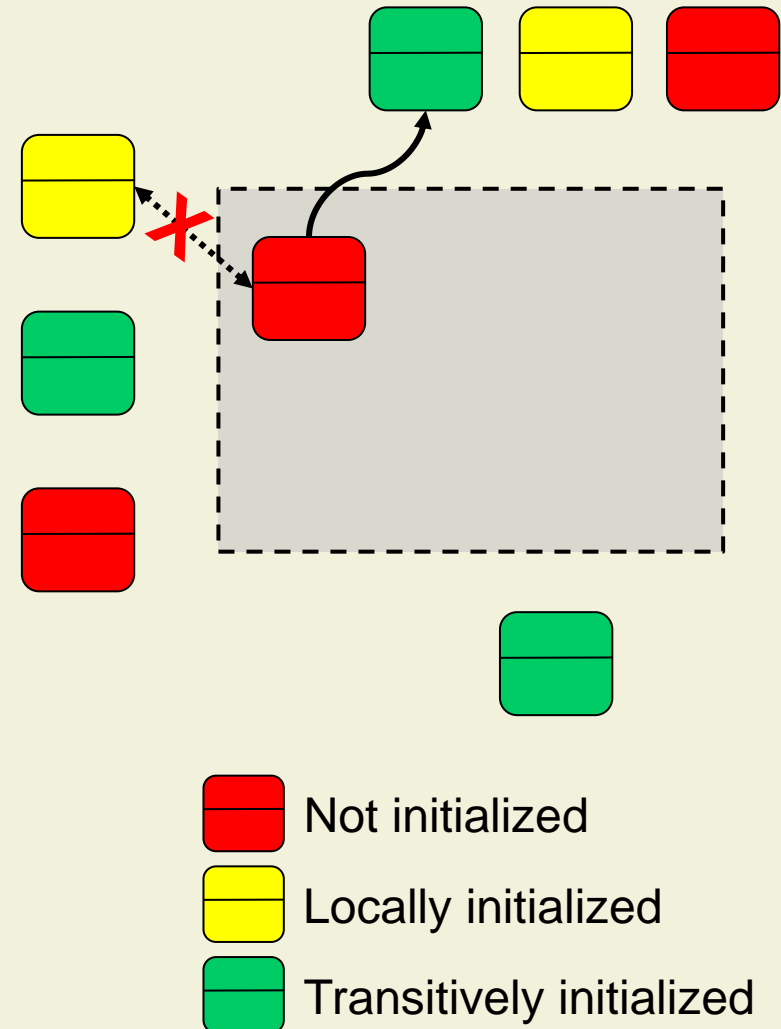
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Object Construction

■ Assumptions

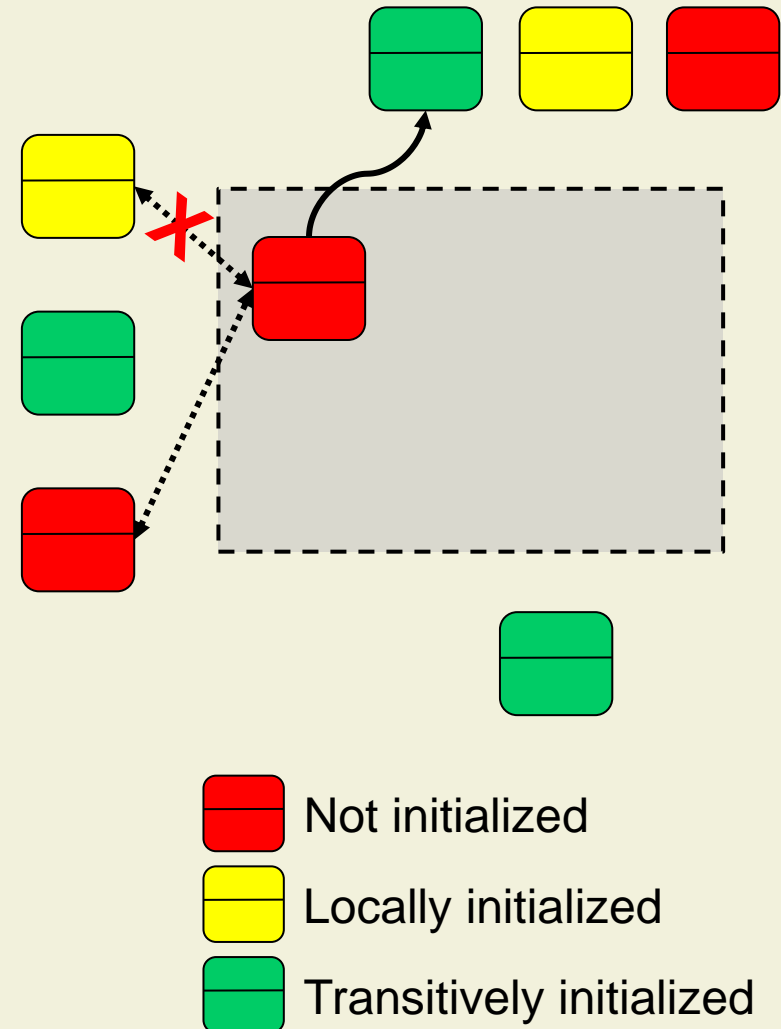
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Object Construction

Assumptions

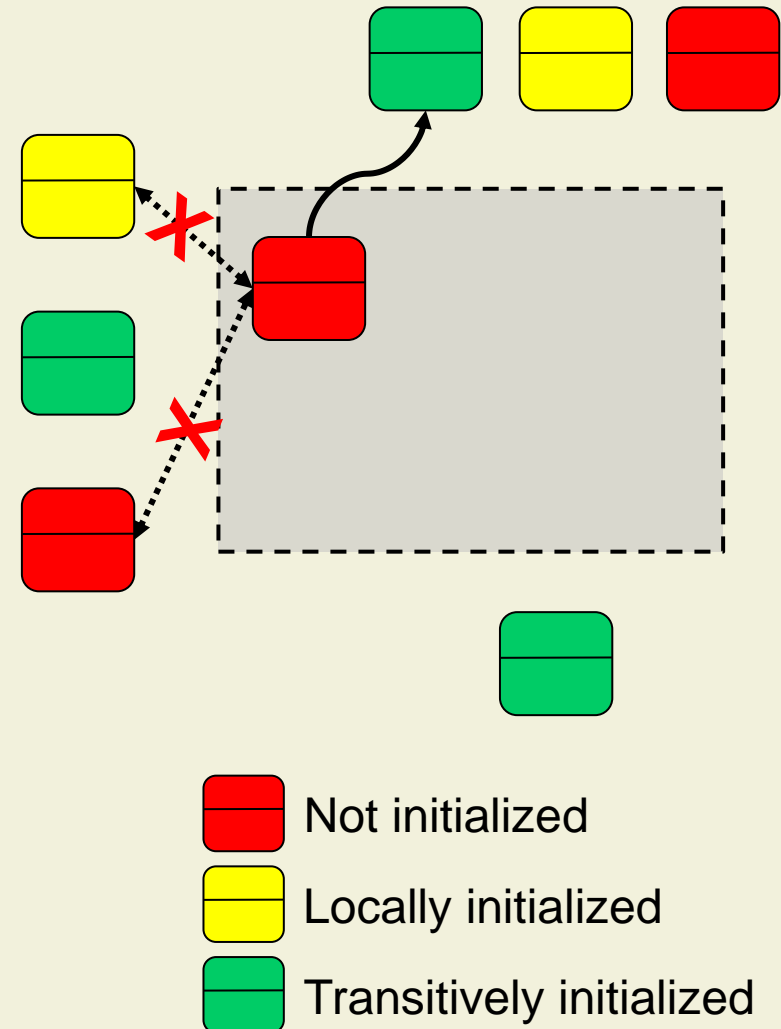
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Object Construction

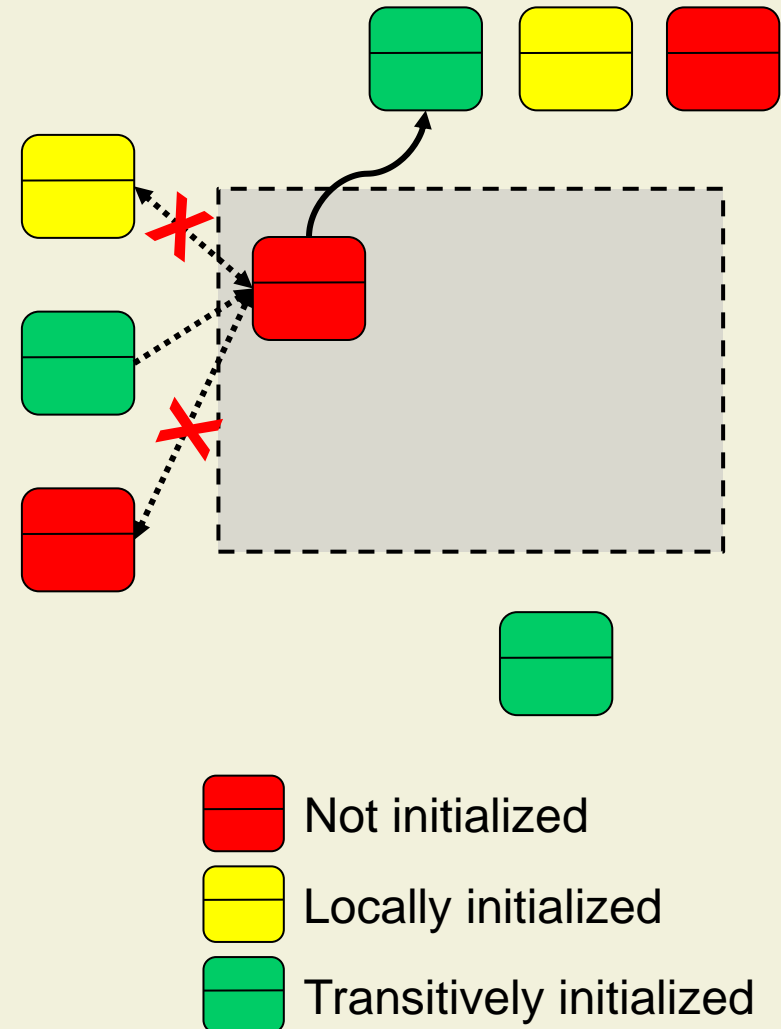
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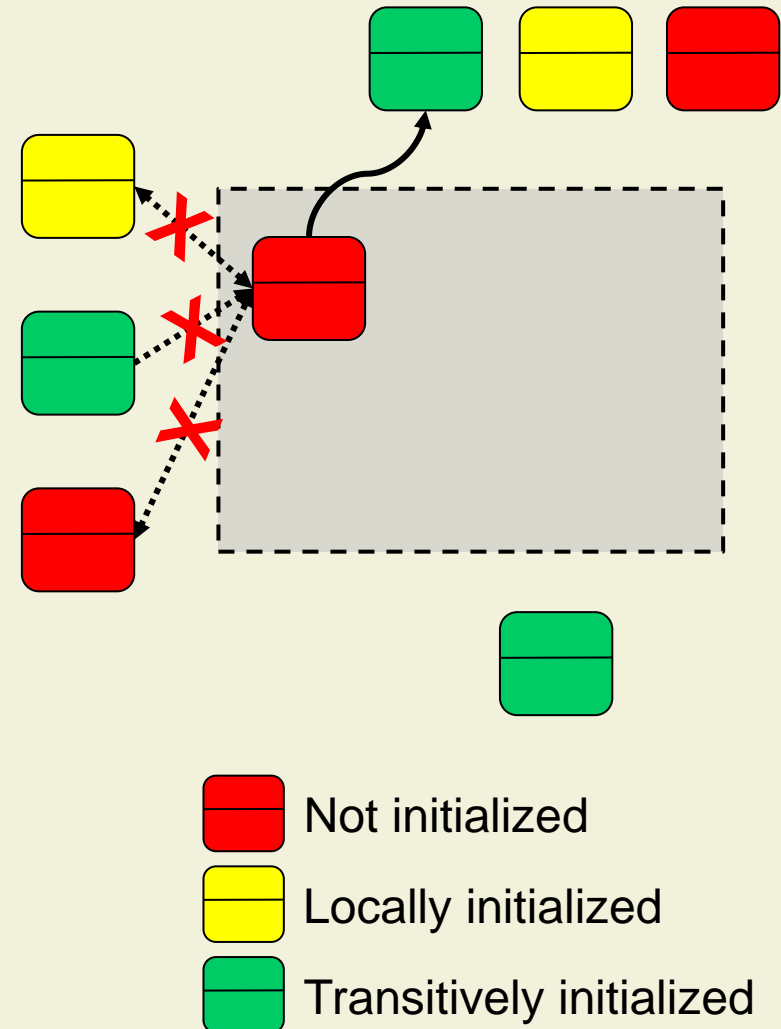
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Object Construction

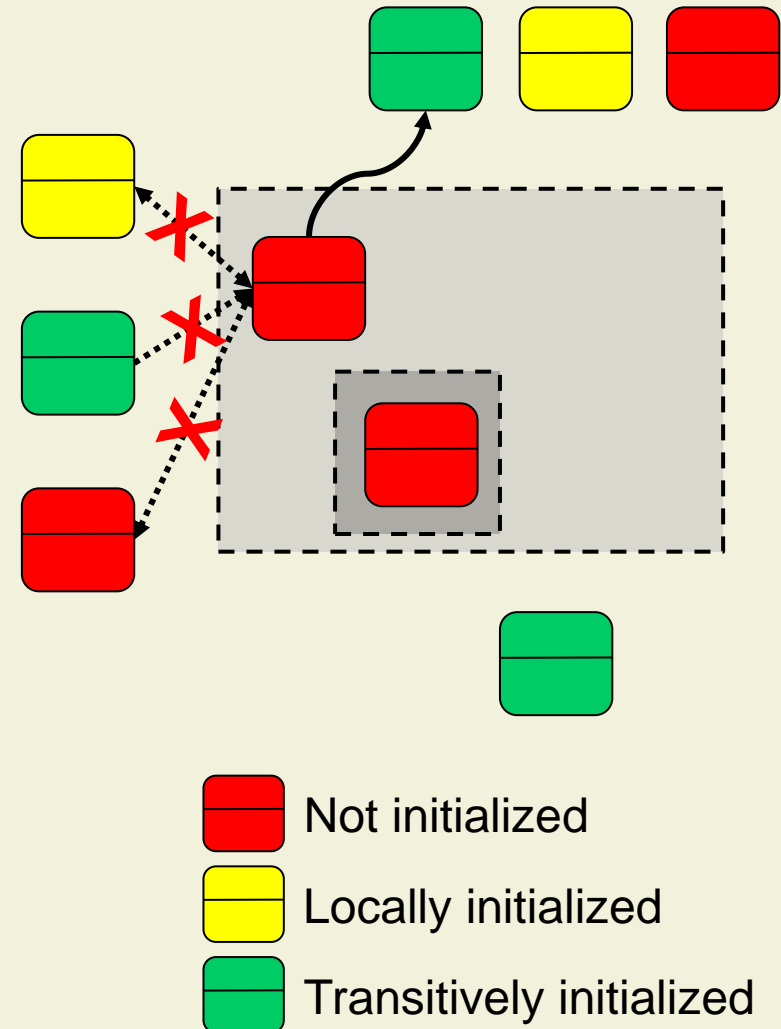
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Object Construction

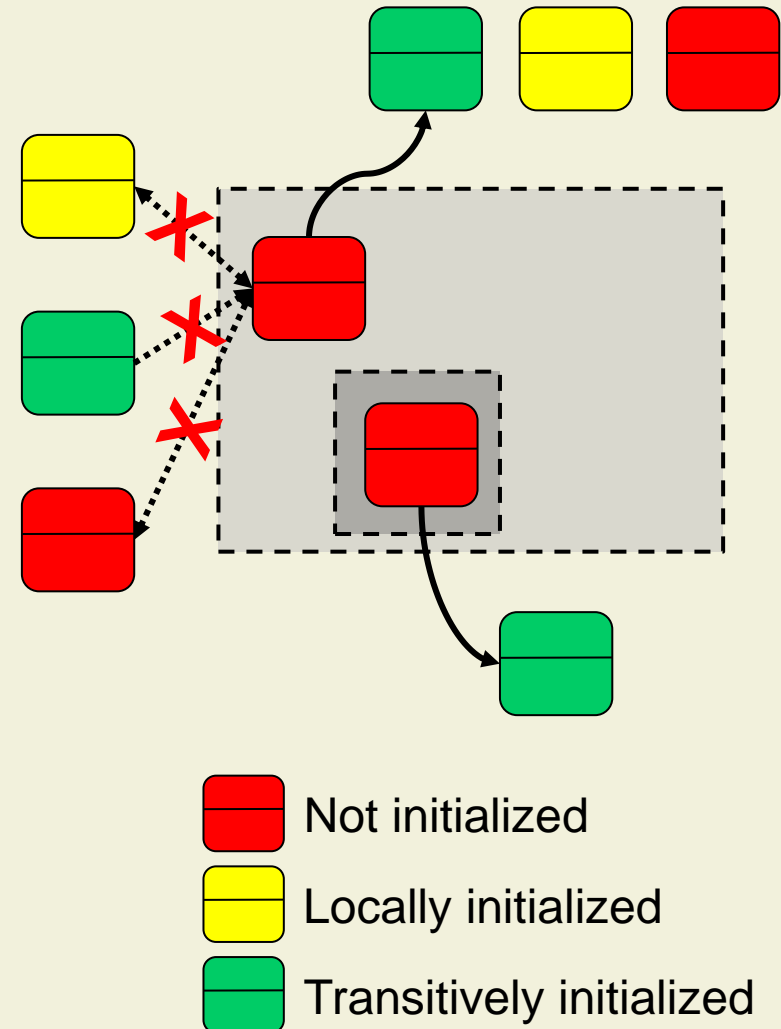
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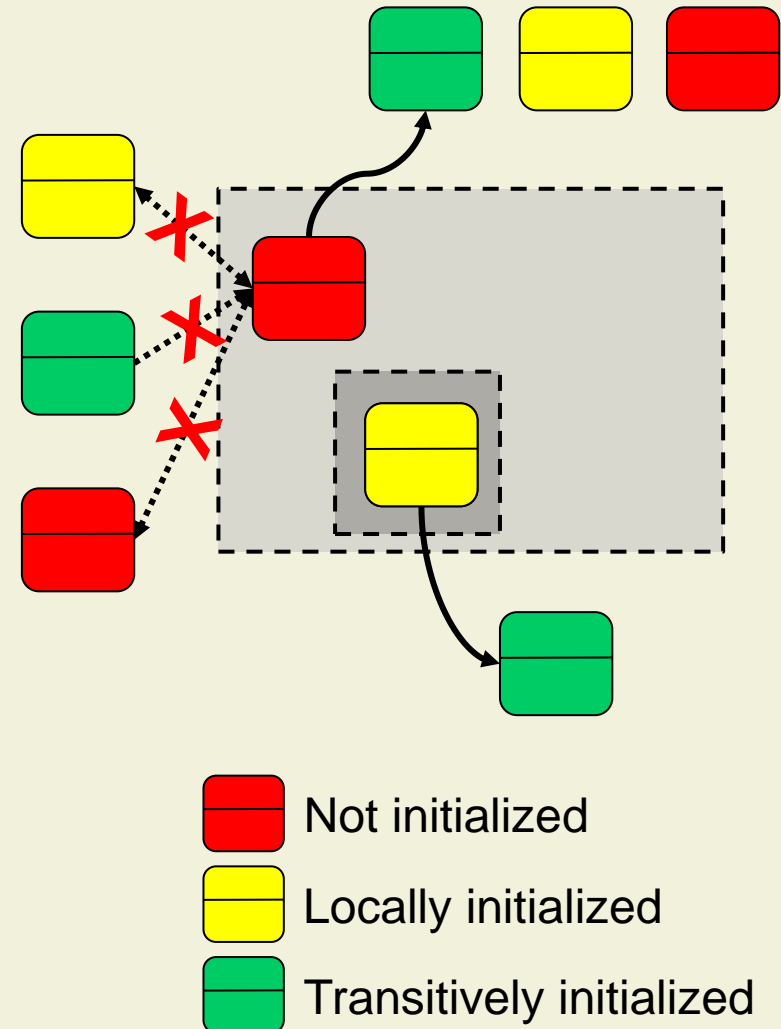
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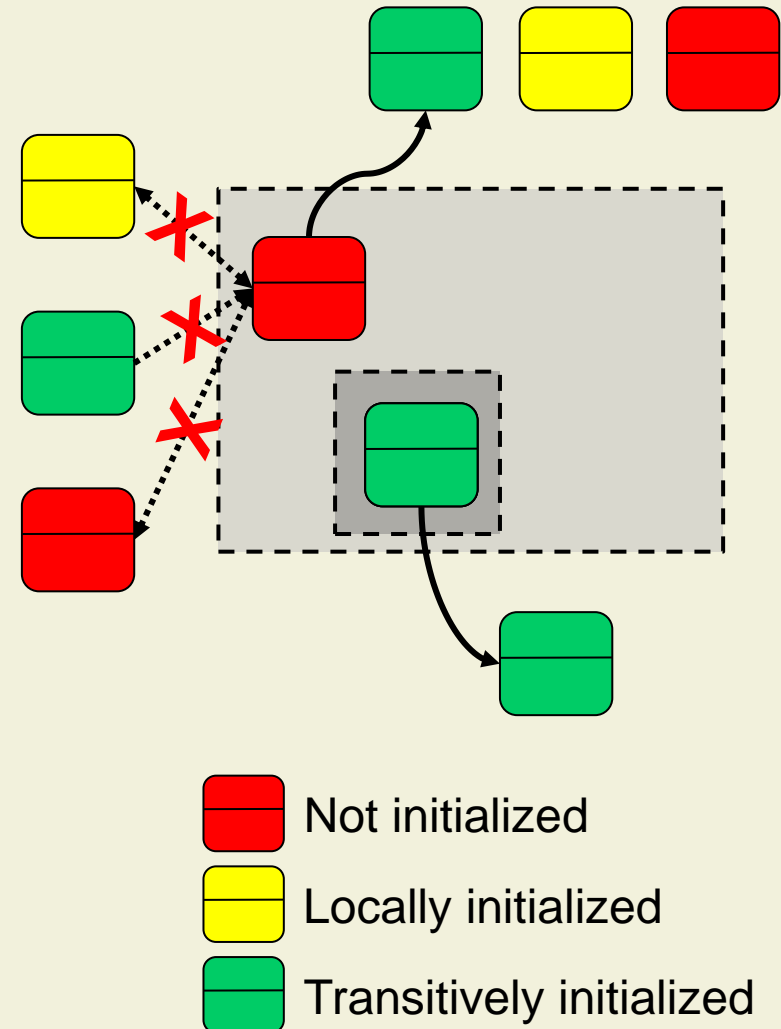
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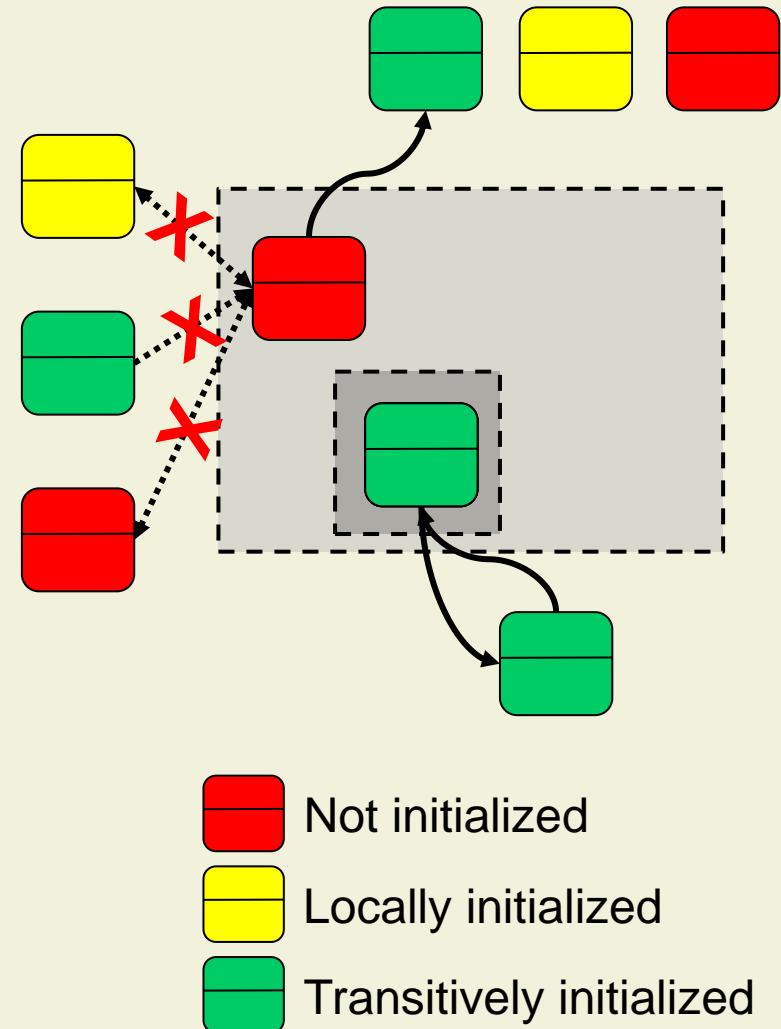
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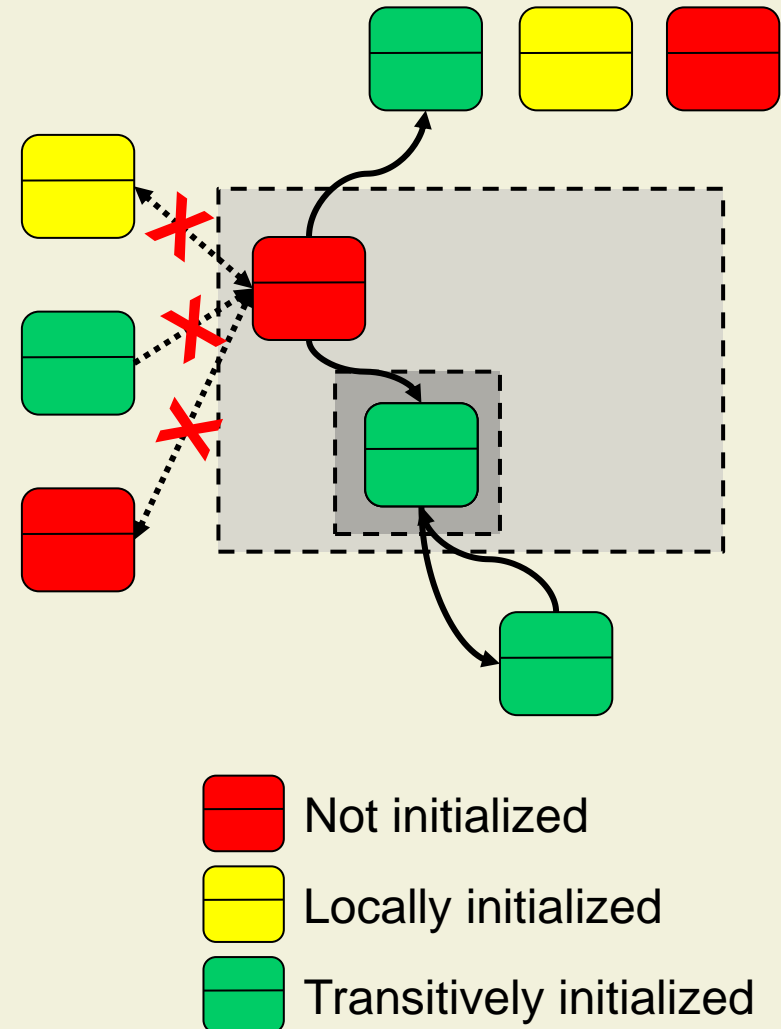
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Object Construction

Assumptions

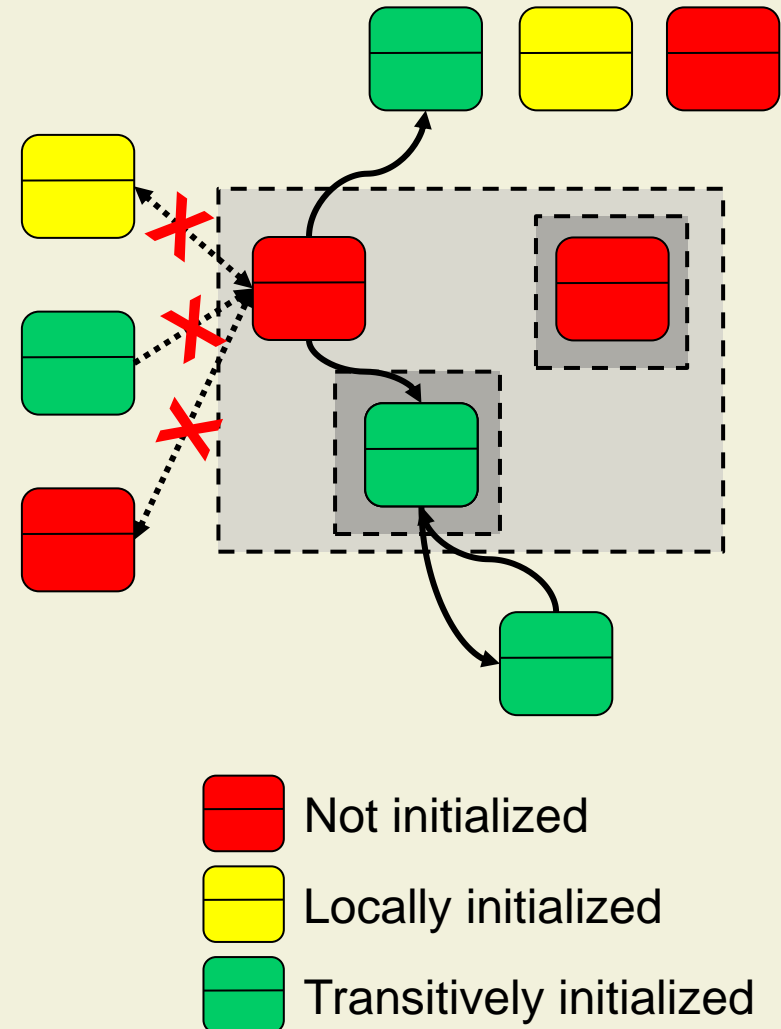
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Object Construction

■ Assumptions

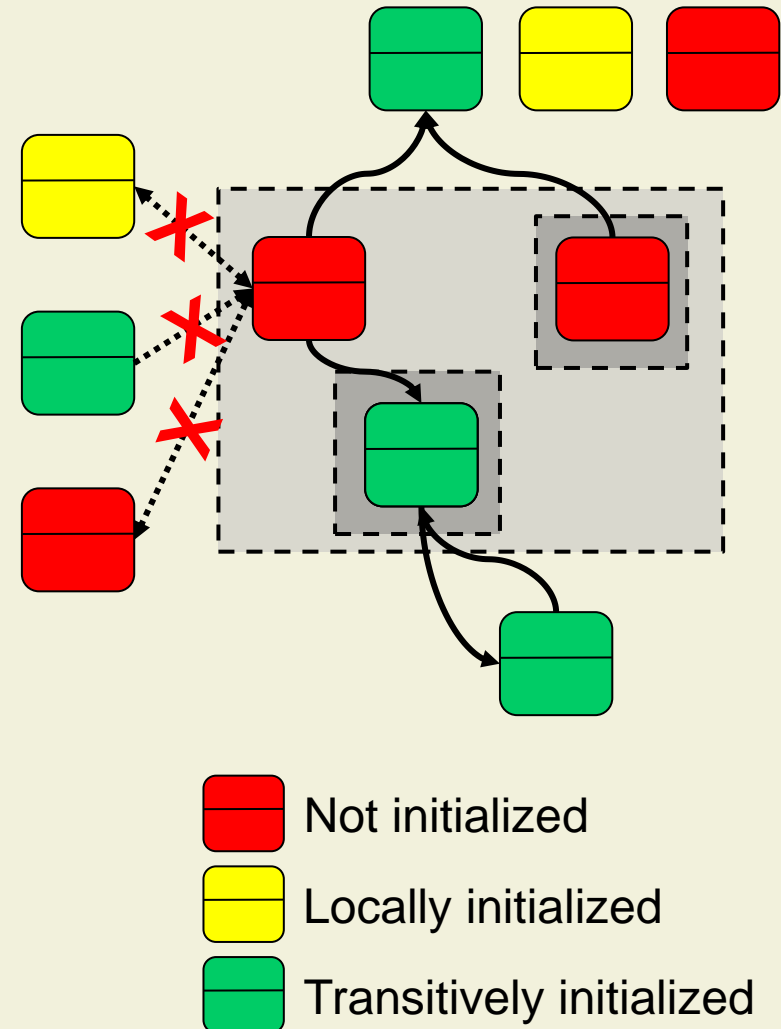
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Object Construction

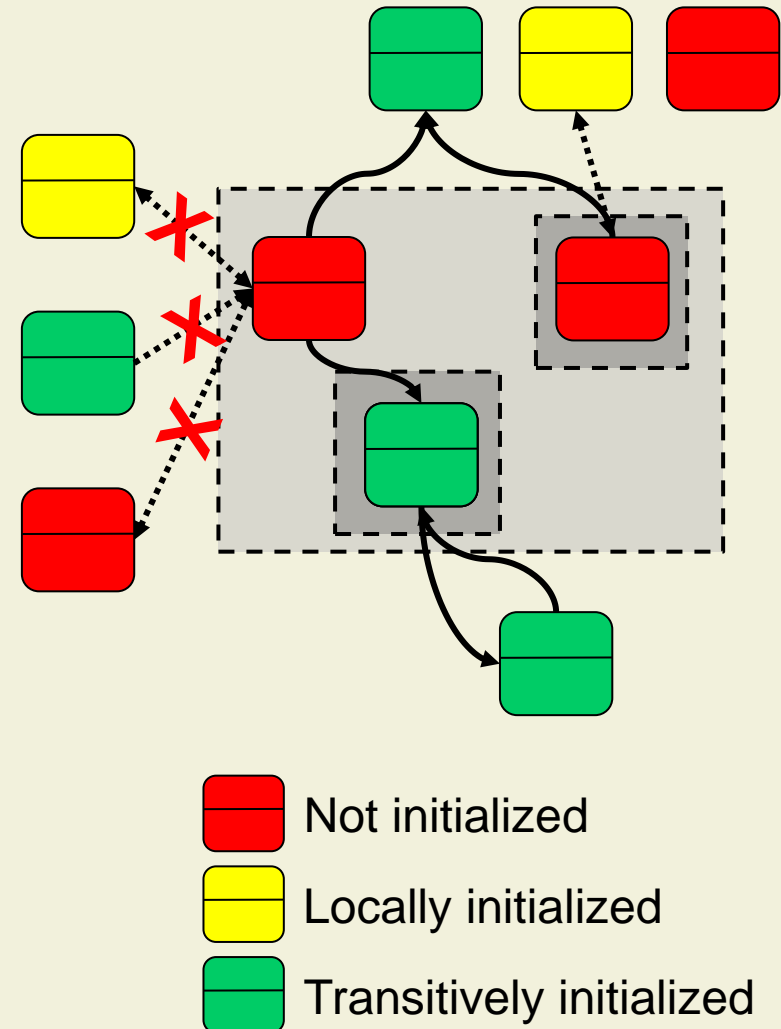
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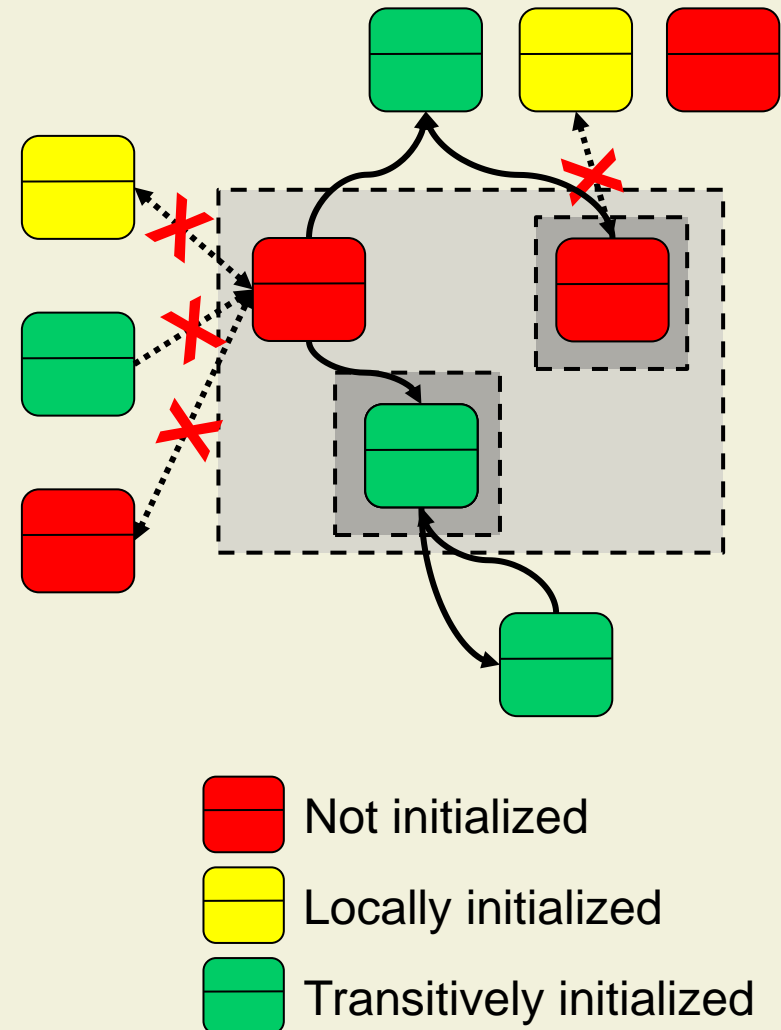
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Object Construction

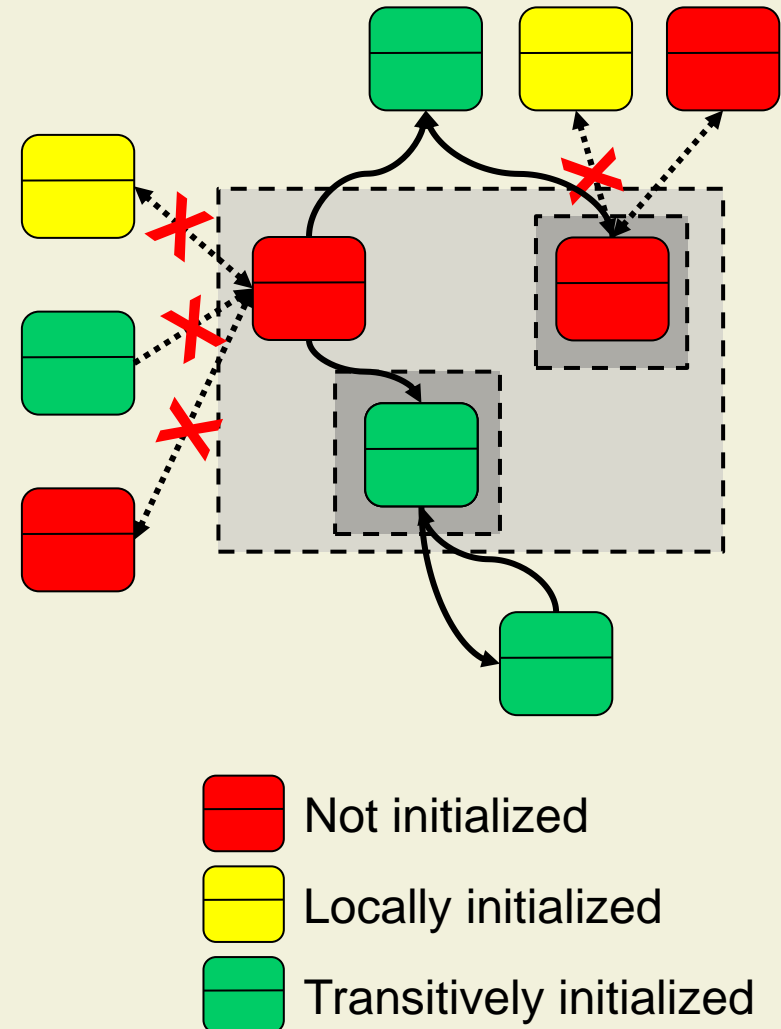
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Object Construction

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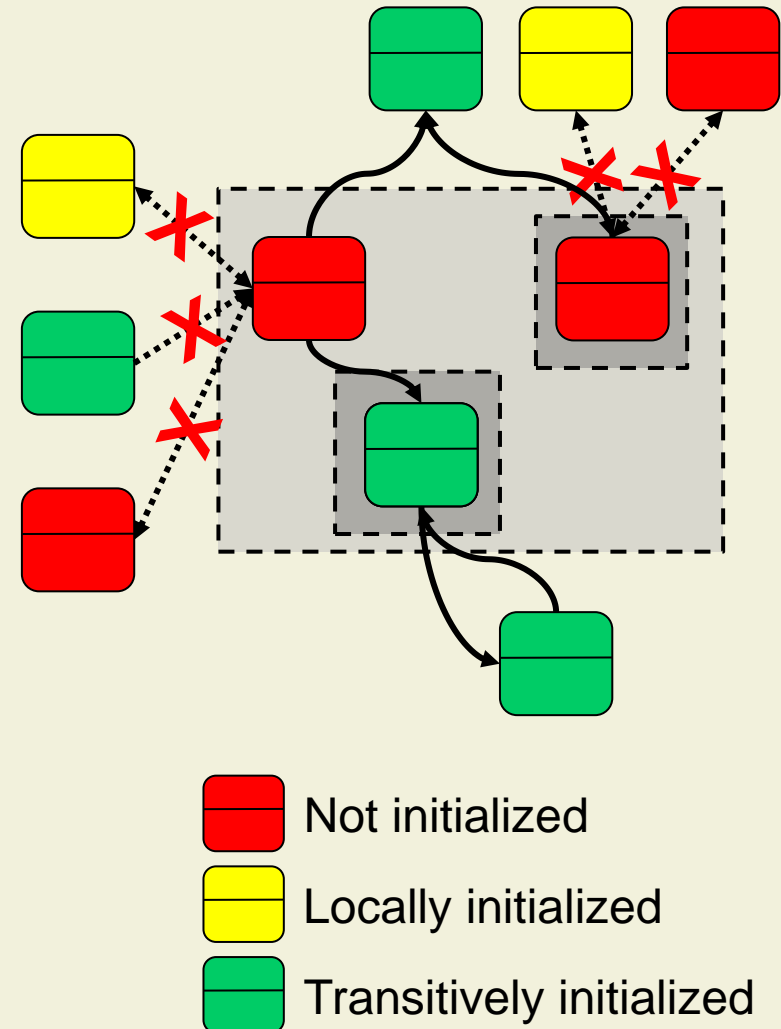
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Object Construction

Assumptions

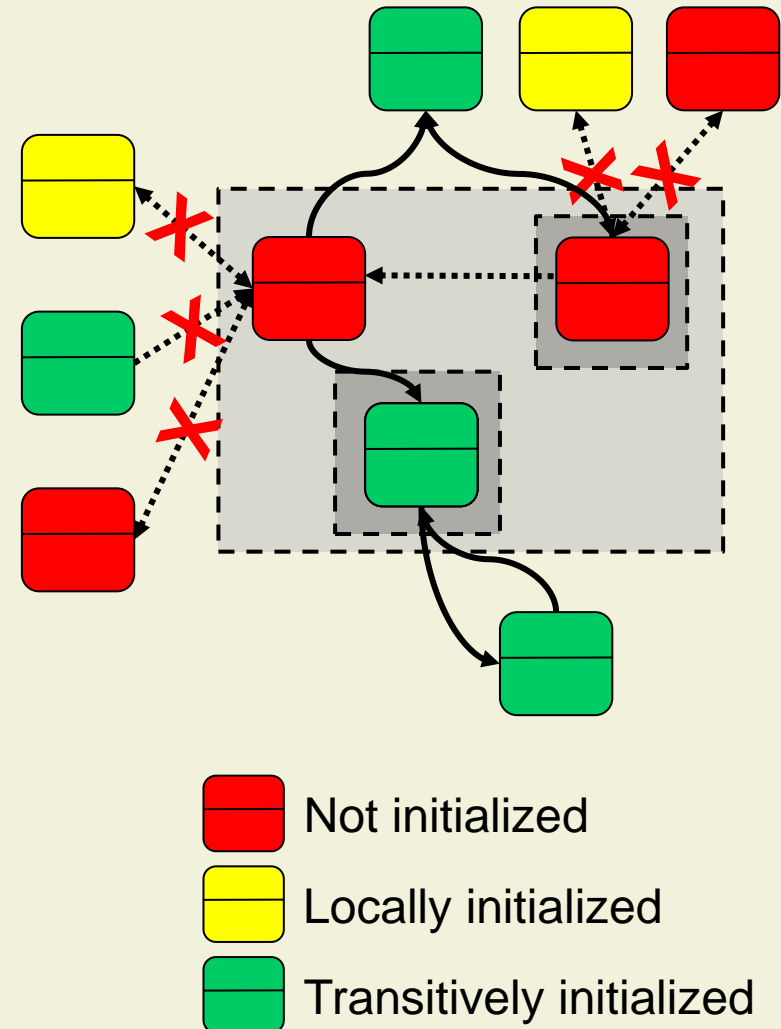
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Object Construction

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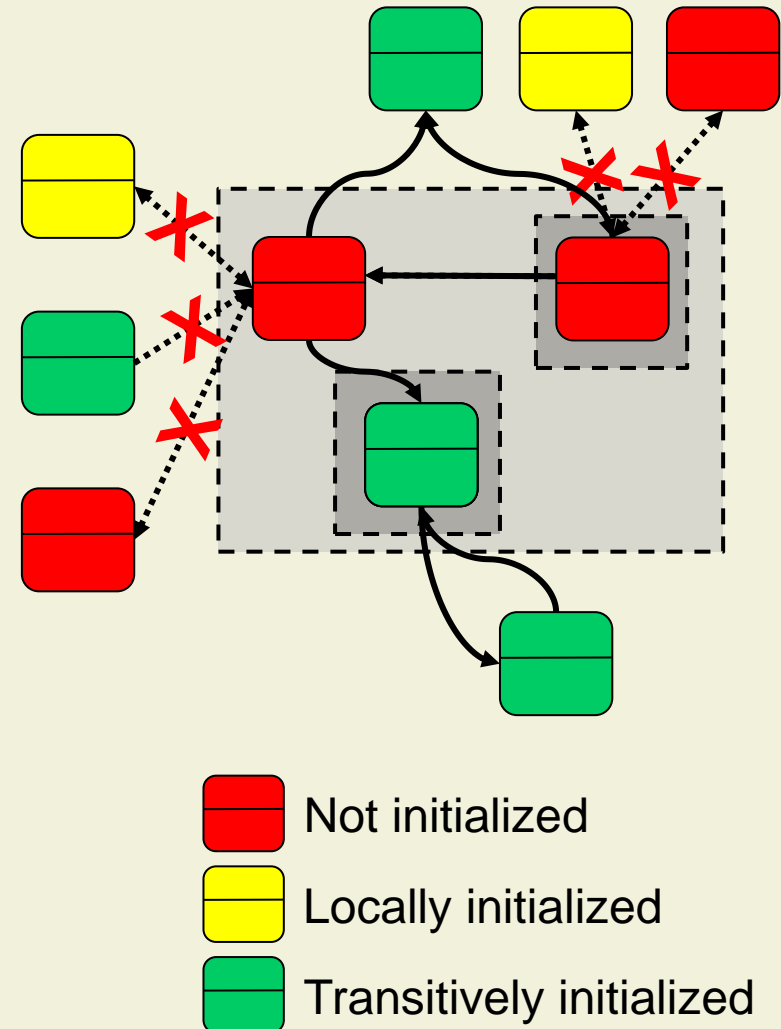
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Object Construction

Assumptions

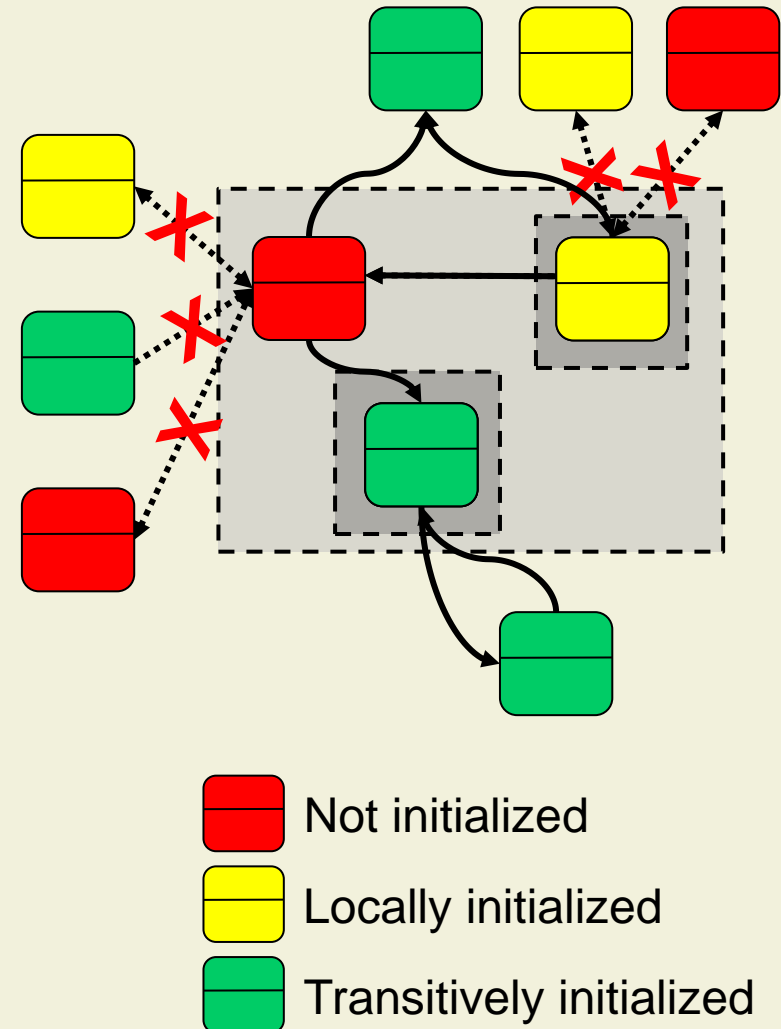
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Object Construction

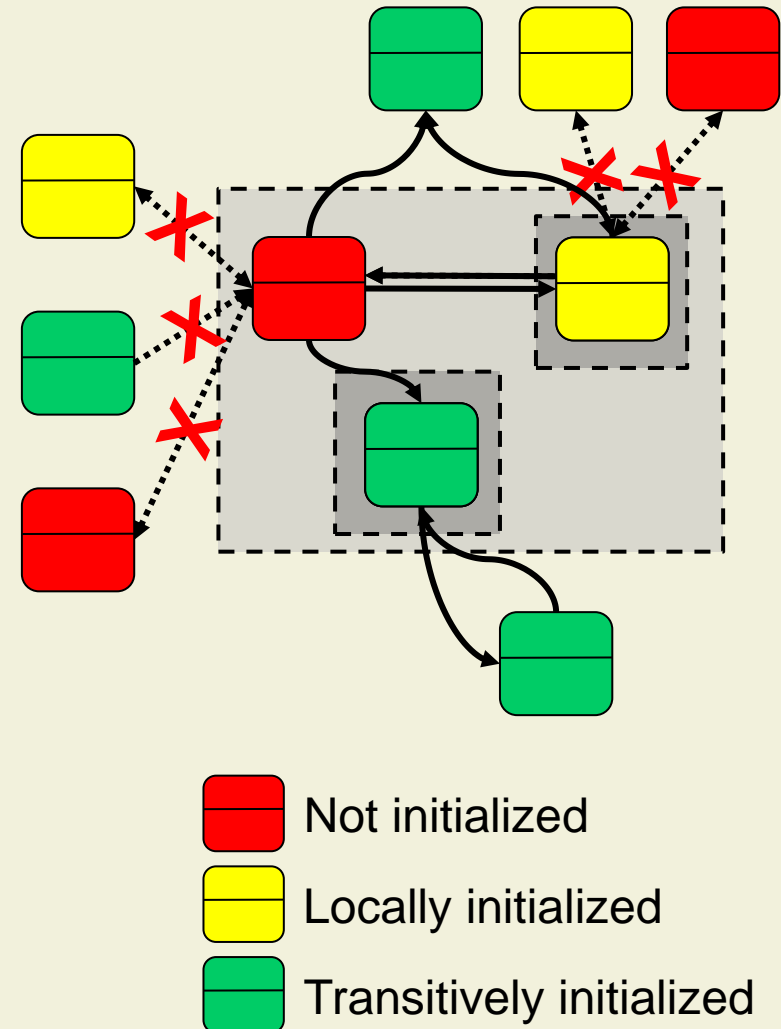
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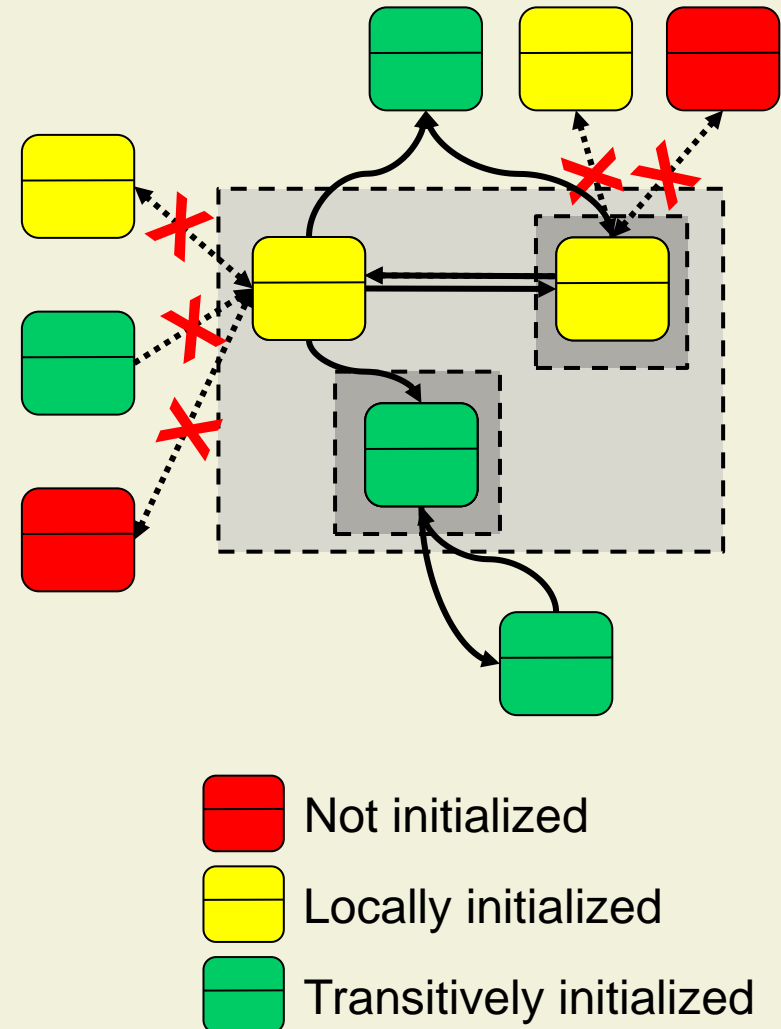
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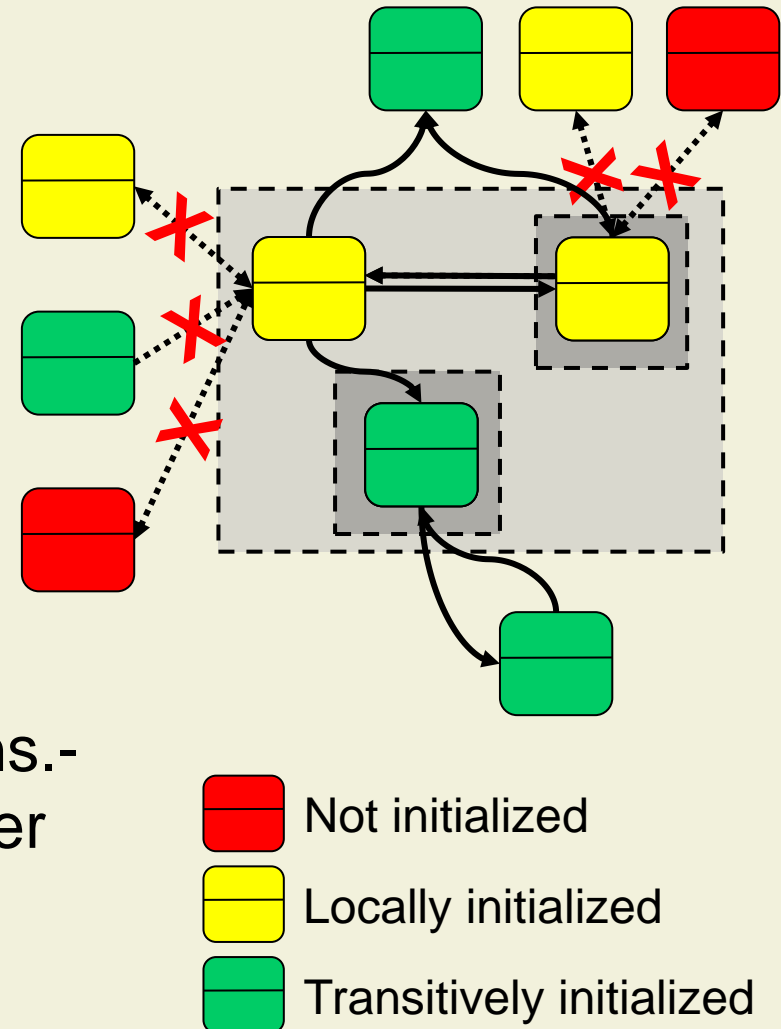
Object Construction

- Assumptions
 - new-expression takes **only committed arguments**
 - Nested new-expressions take **arbitrary arguments**
- After new-expression
 - All new objects are **locally initialized**



Object Construction

- Assumptions
 - new-expression takes **only committed arguments**
 - Nested new-expressions take **arbitrary arguments**
- After new-expression
 - All new objects are **locally initialized**
 - New objects reference only trans.-initialized objects and each other



- Assumptions

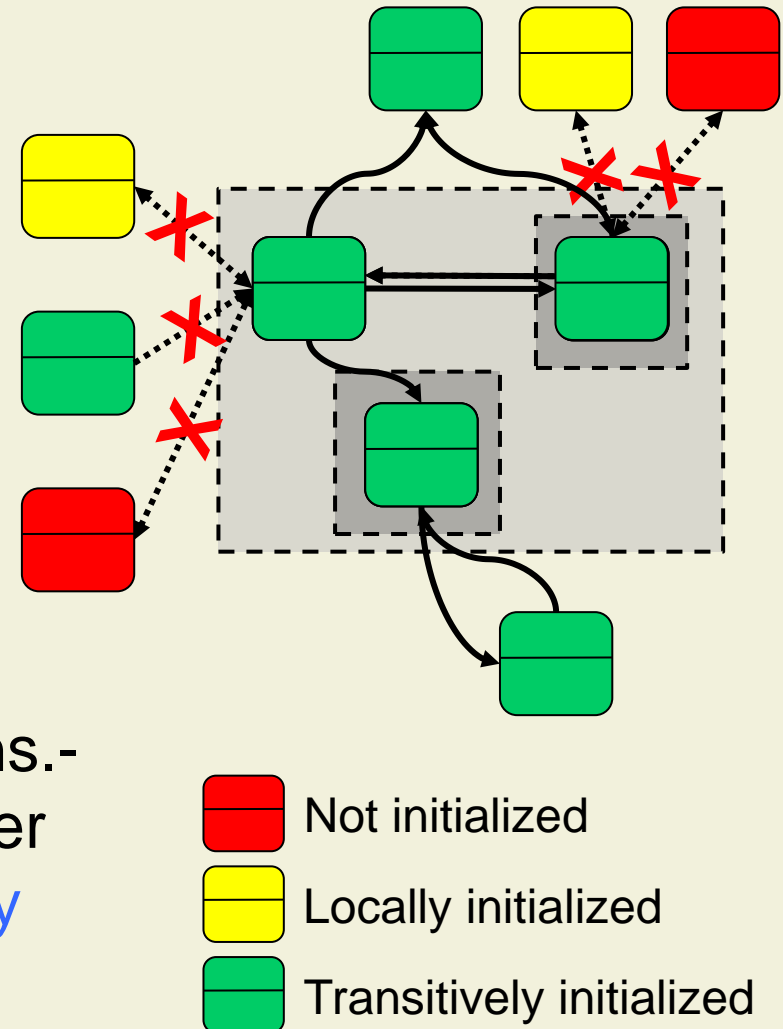
- After new-expression

-

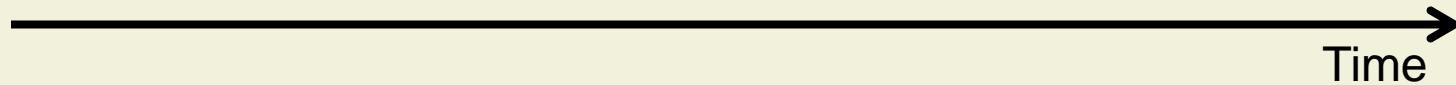
Peter Müller – Concepts of Object-Oriented Programming

Object Construction

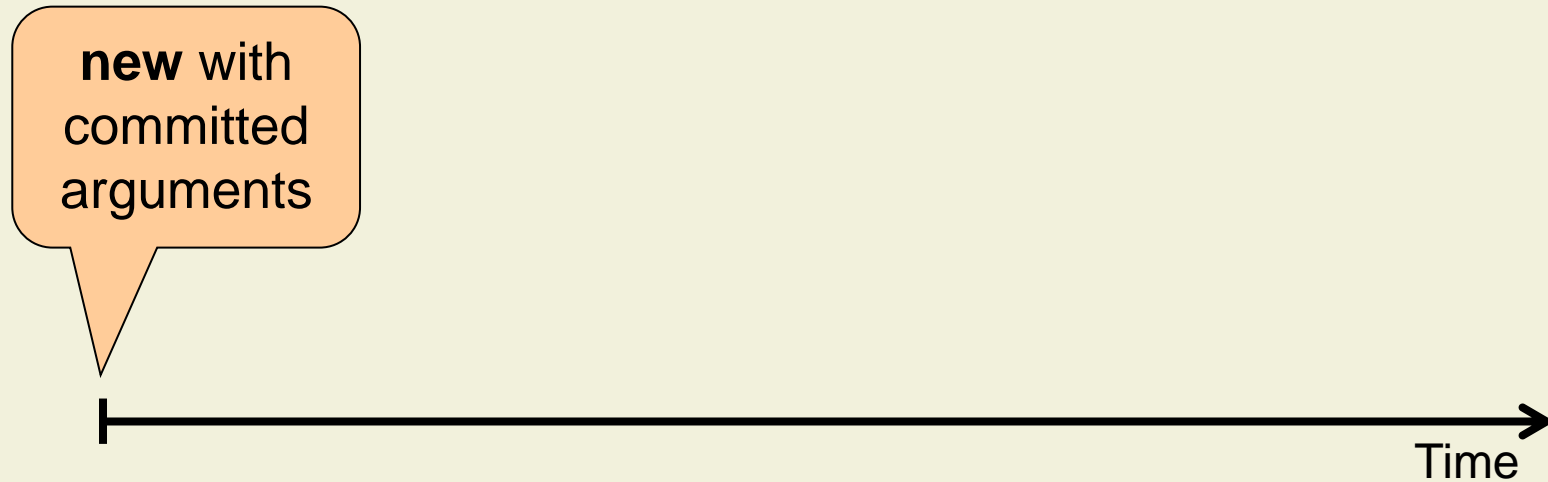
- Assumptions
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- After new-expression
 - All new objects are **locally initialized**
 - New objects reference only trans.-initialized objects and each other
 - **All** new objects are **transitively initialized**



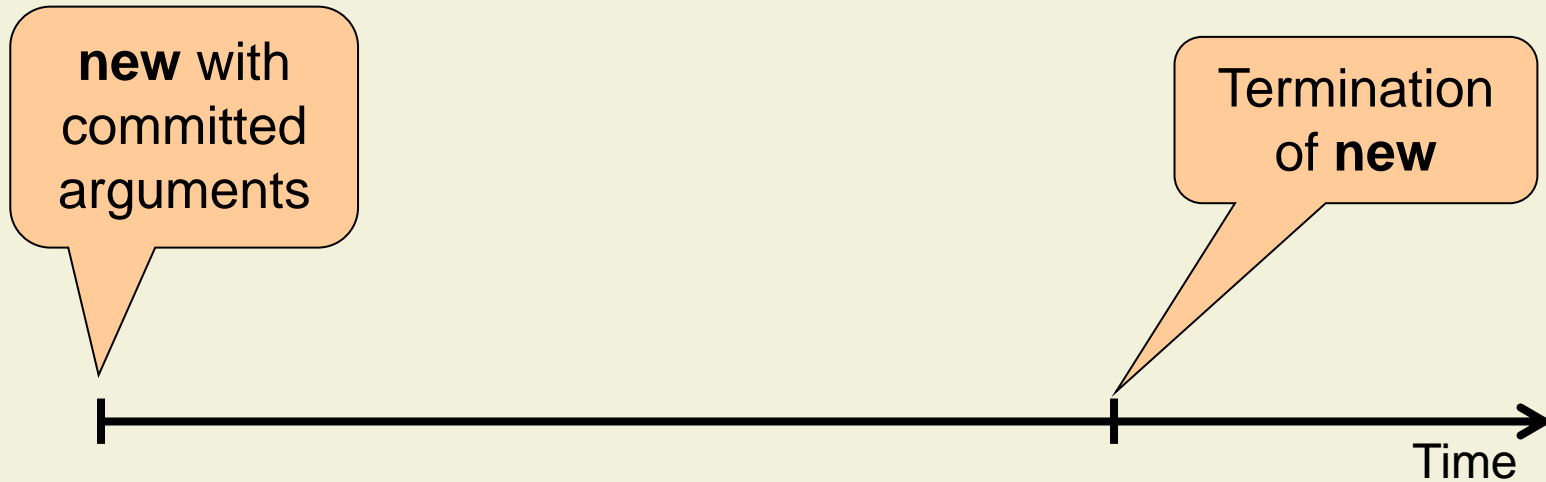
Completing Object Construction



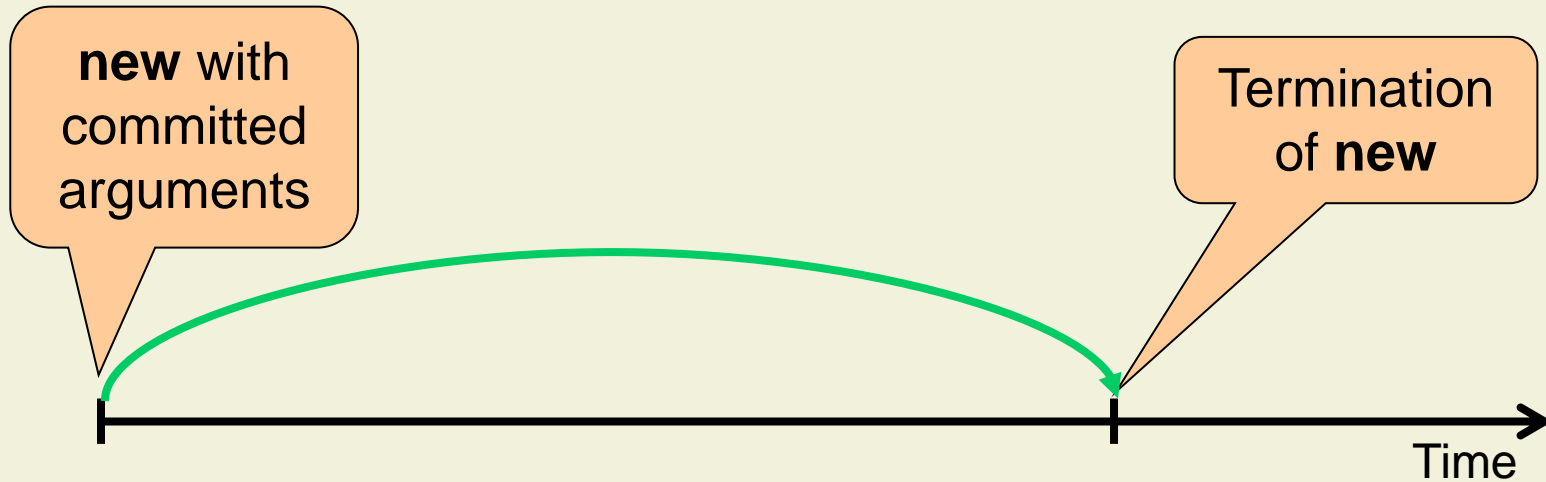
Completing Object Construction



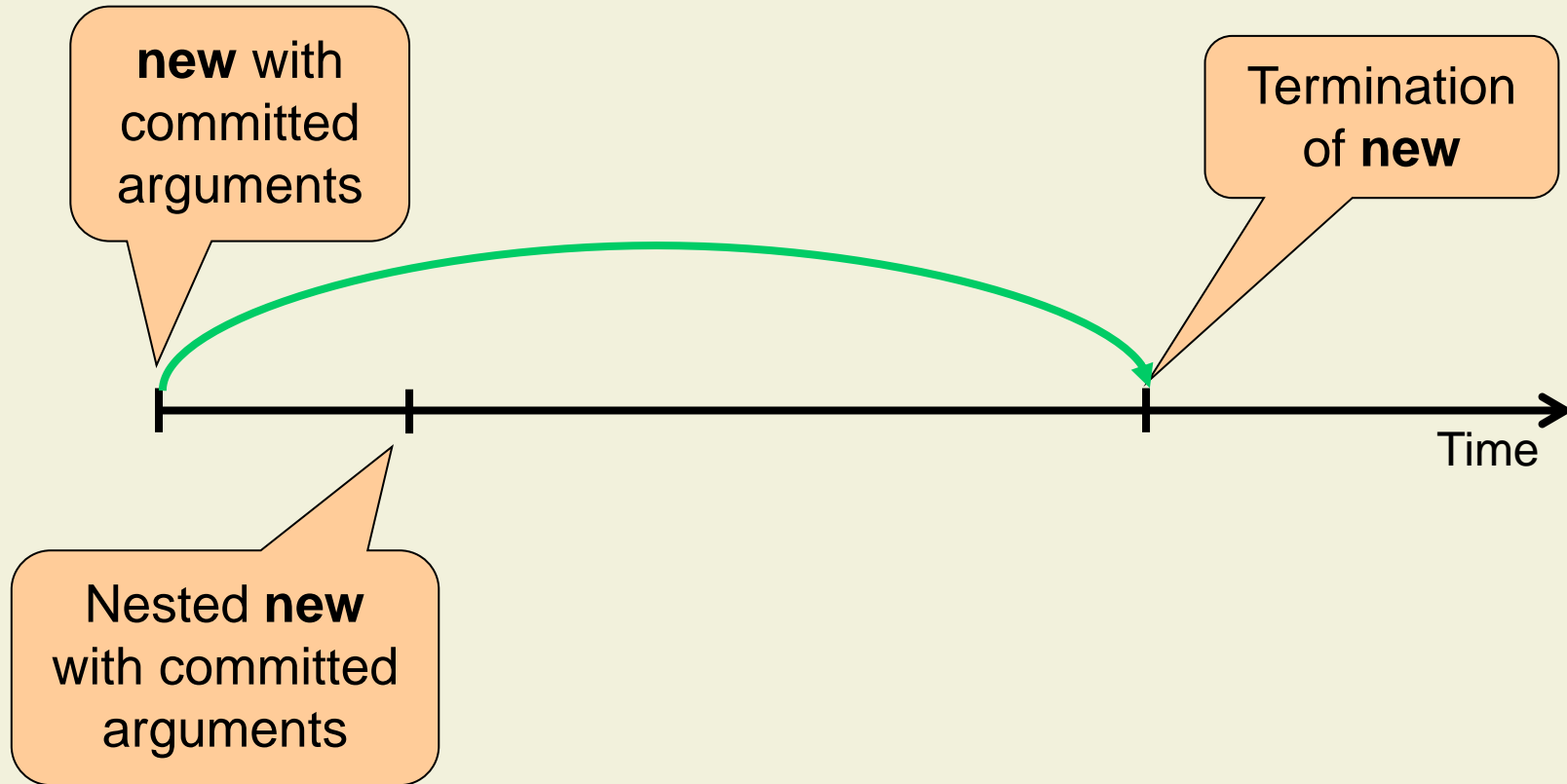
Completing Object Construction



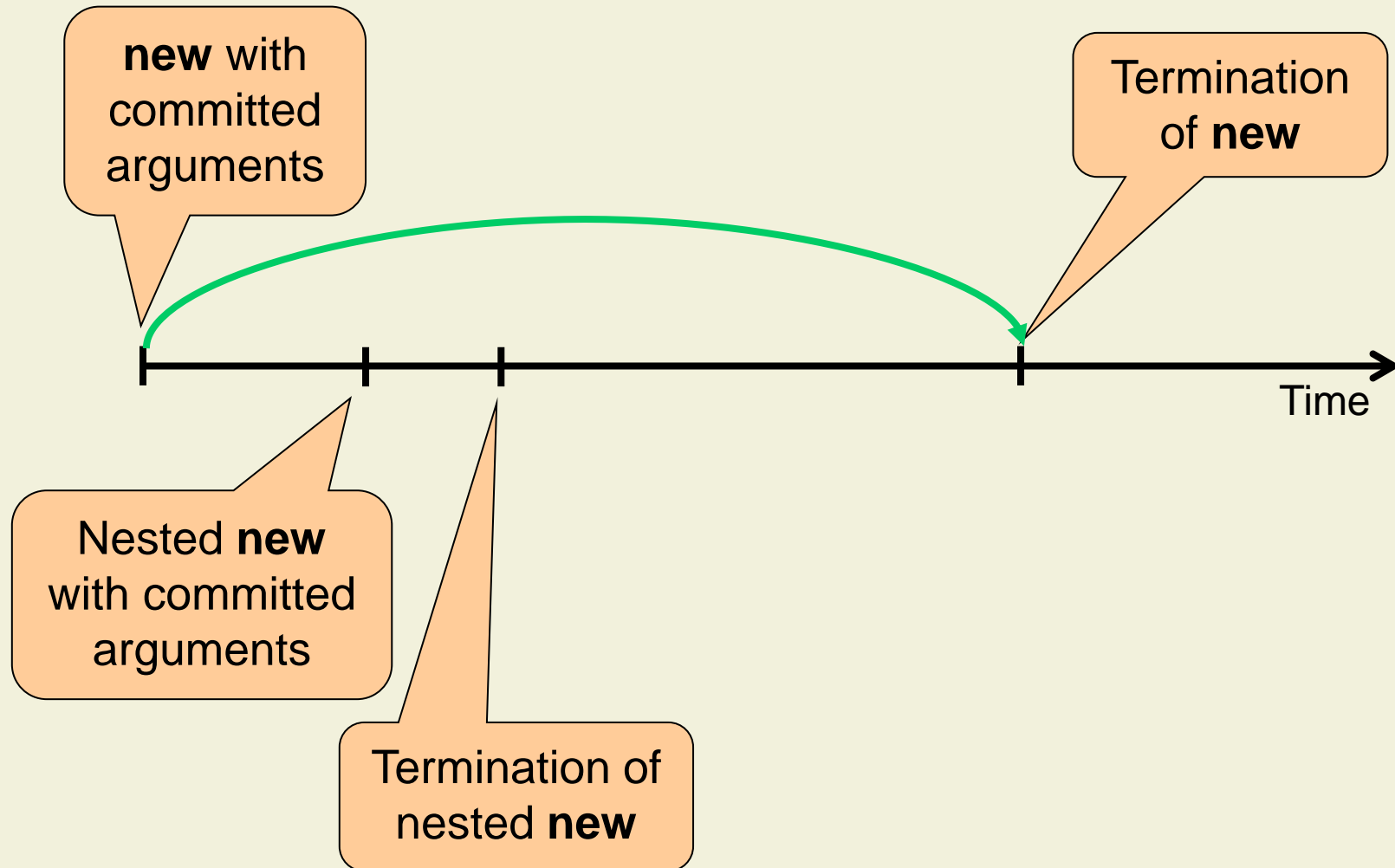
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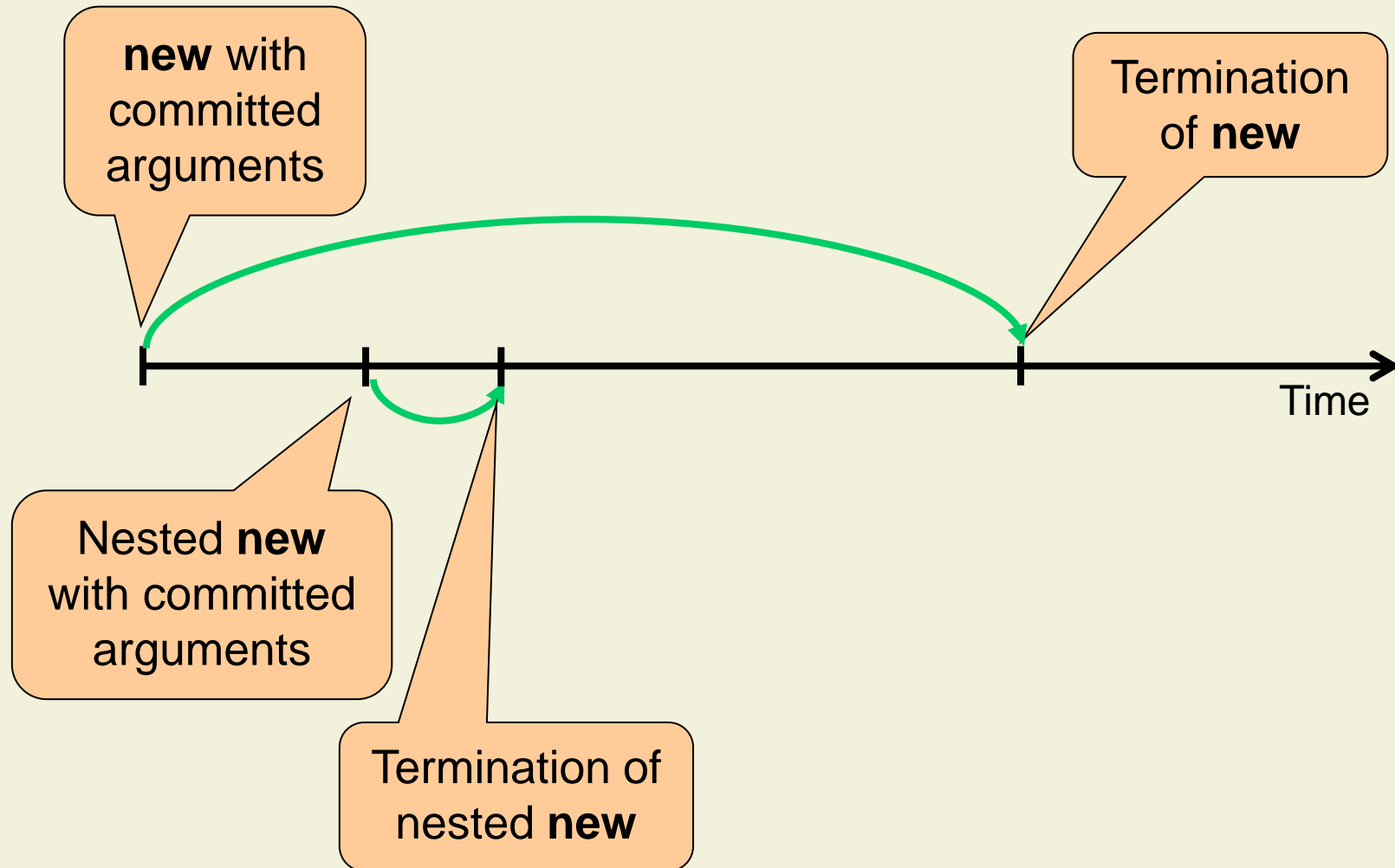
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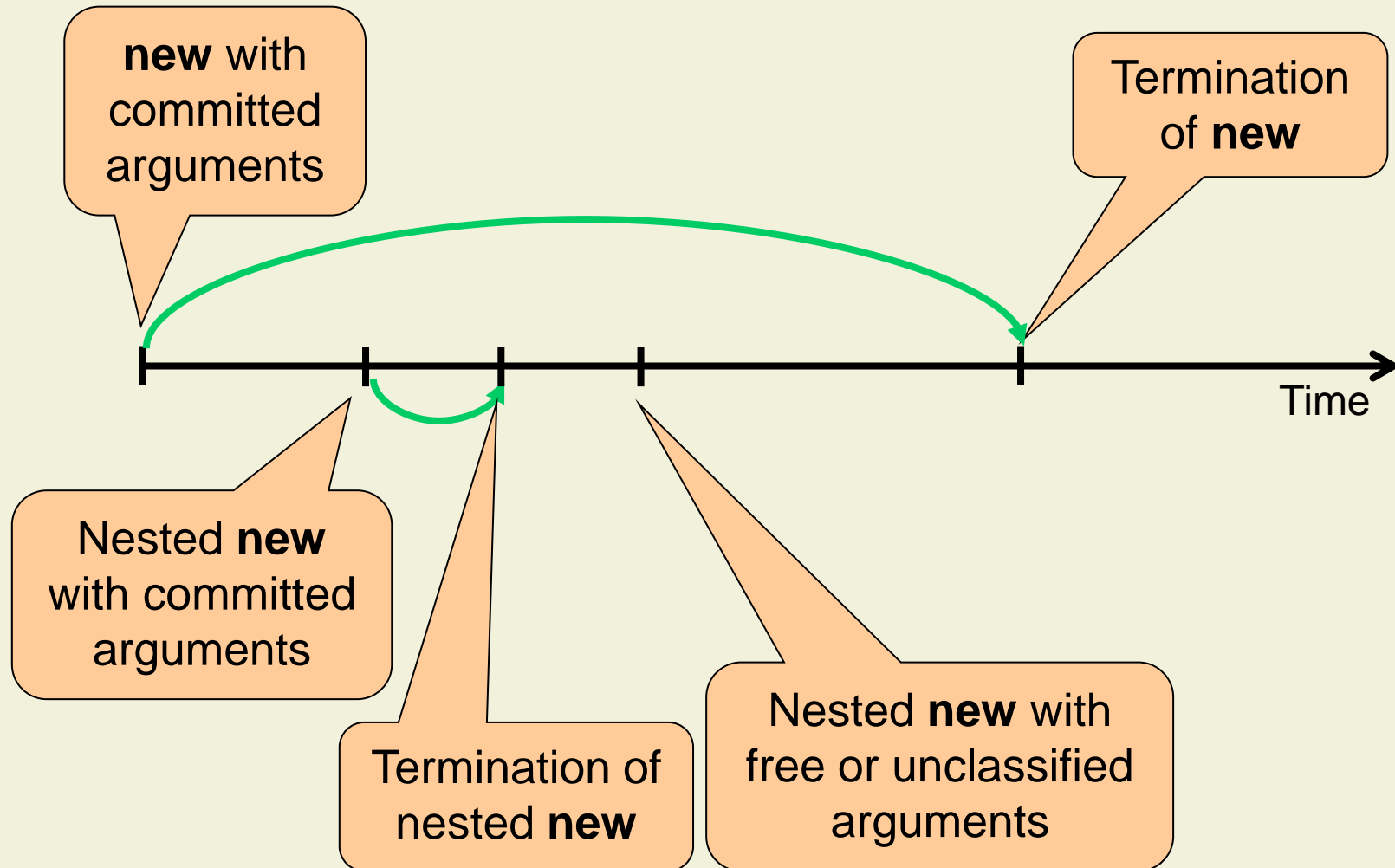
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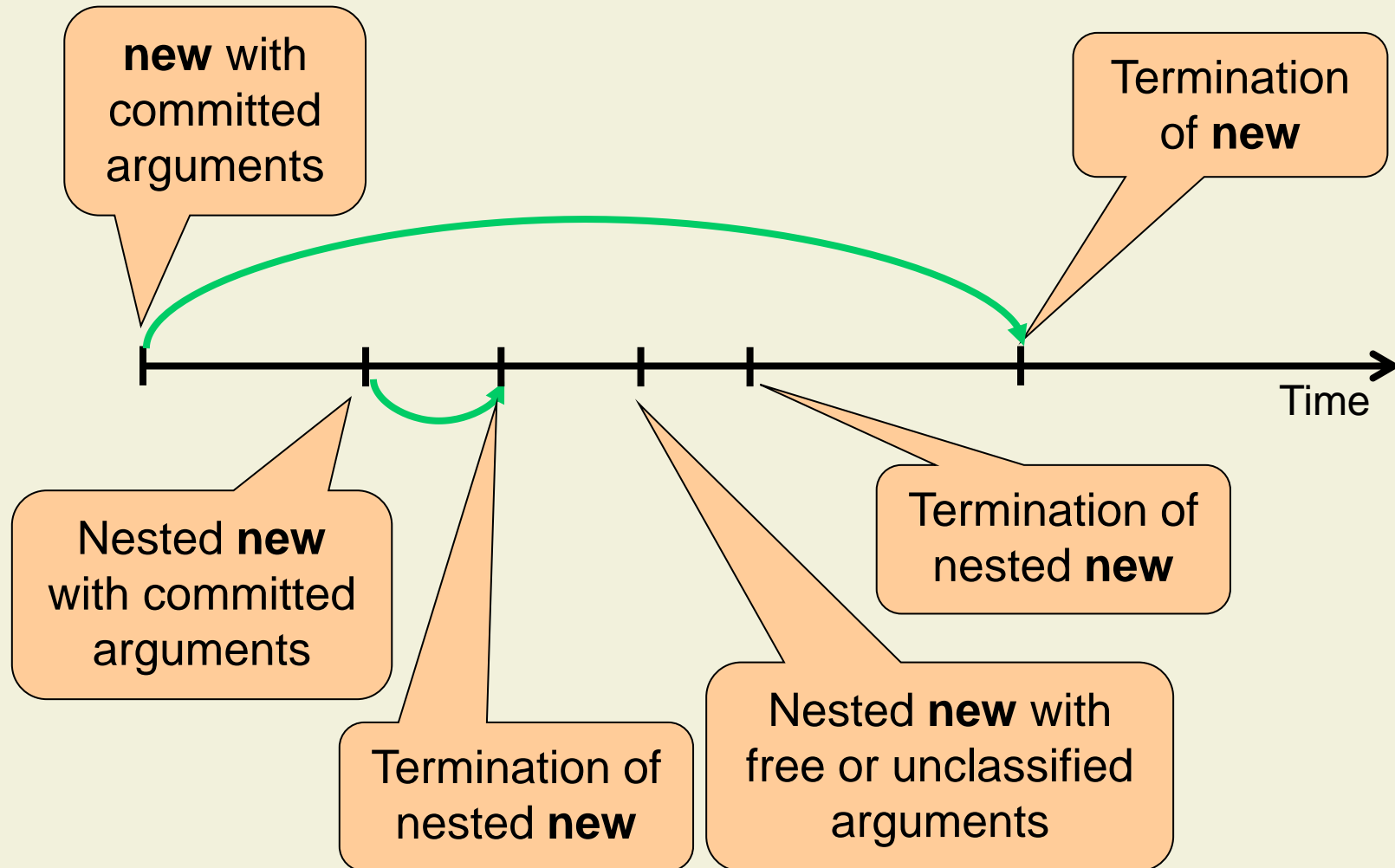
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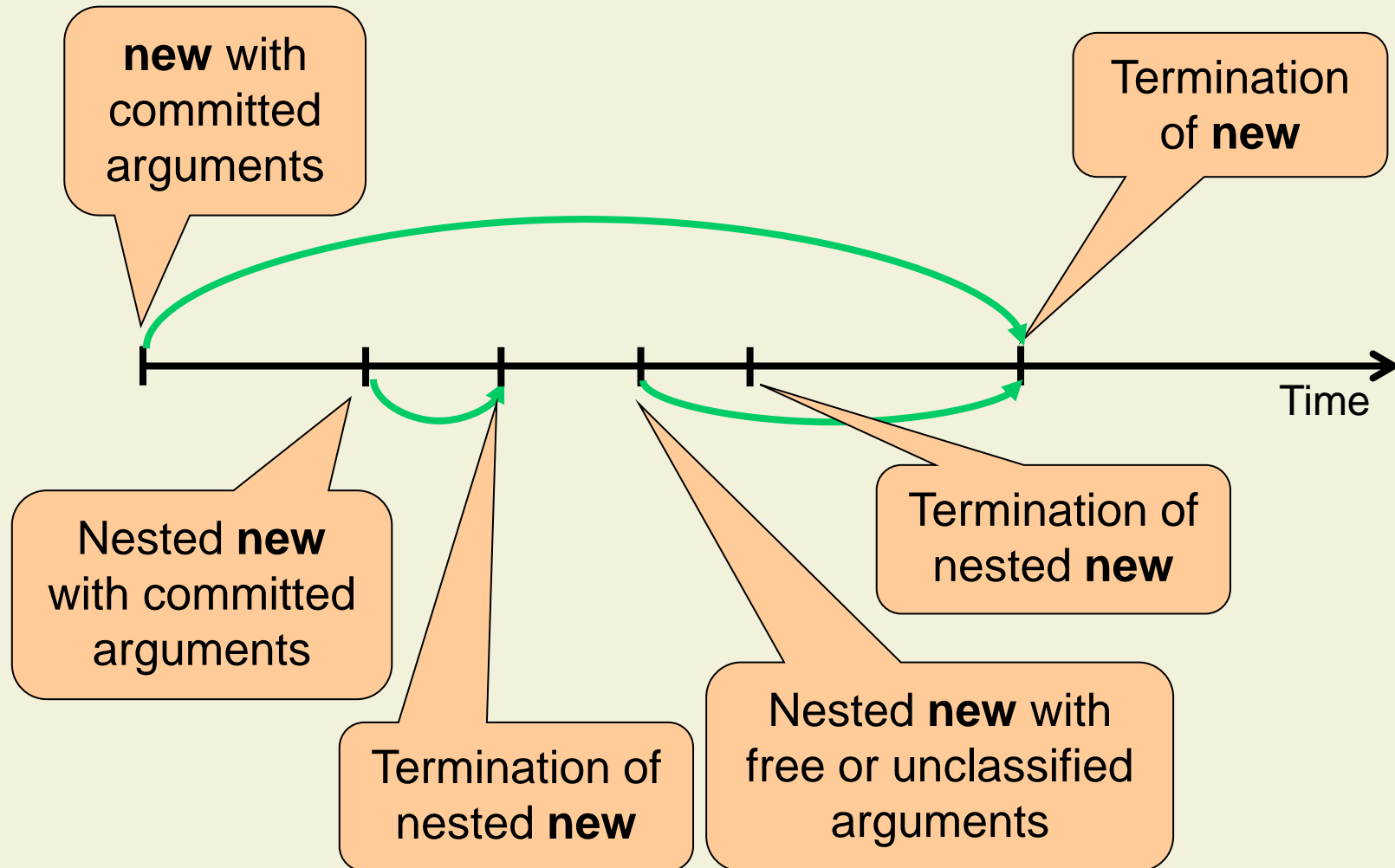
Completing Object Construction



Completing Object Construction



Completing Object Construction



Type Rules: new-Expressions

- An expression **new** C(e_i) is well-typed if
 - All e_i are well-typed
 - Class C contains a constructor with suitable parameter types
- The type of **new** C(e_i) is
 - committed C! if the static types of all e_i are committed
 - free C! otherwise

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 - committed C! if the **static types of all e_i are committed**
 - free C! otherwise

```
class Demo {  
  C! myC;  
  Demo( ) {  
    free C! c = new C( this );  
    c.foo( );  
    myC = c;  
  }  
}
```

Cyclic Structures: Example

```
class List {  
    List! next; // cyclic  
  
    List( int n ) {  
        if( n == 1 )  
            next = this;  
        else  
            next = new List( this, n );  
    }  
  
    List( free List! last, int n ) {  
        if( n == 2 )  
            next = last;  
        else  
            next = new List( last, n-1 );  
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Cyclic Structures: Example

```
l = new List( 3 );
```

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class List {  
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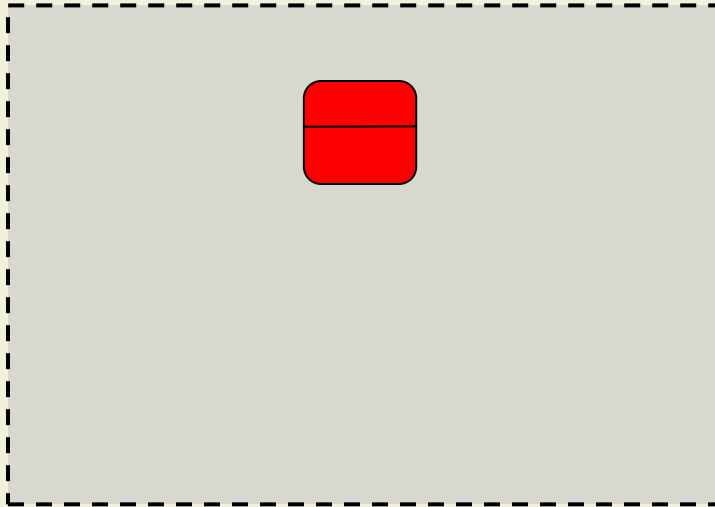
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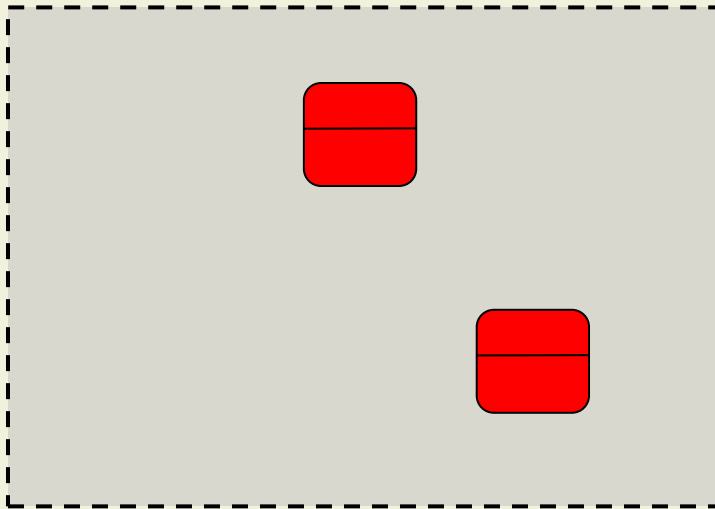
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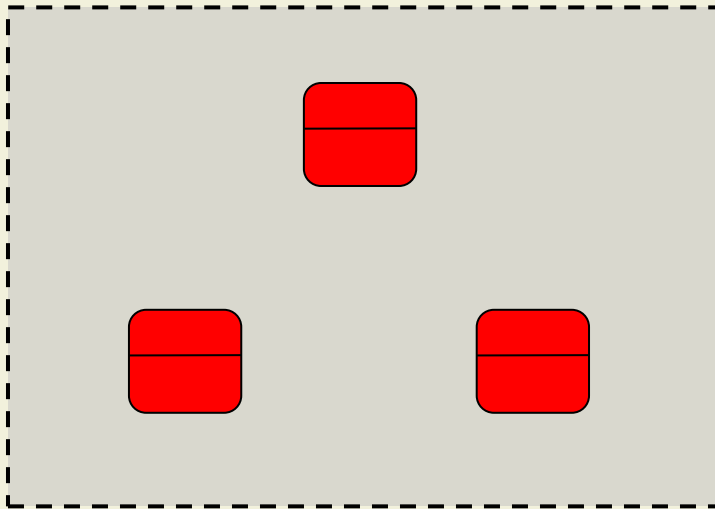
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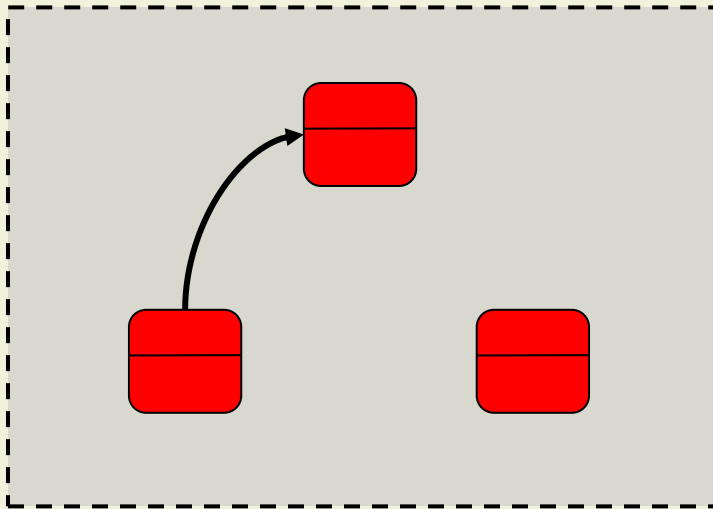
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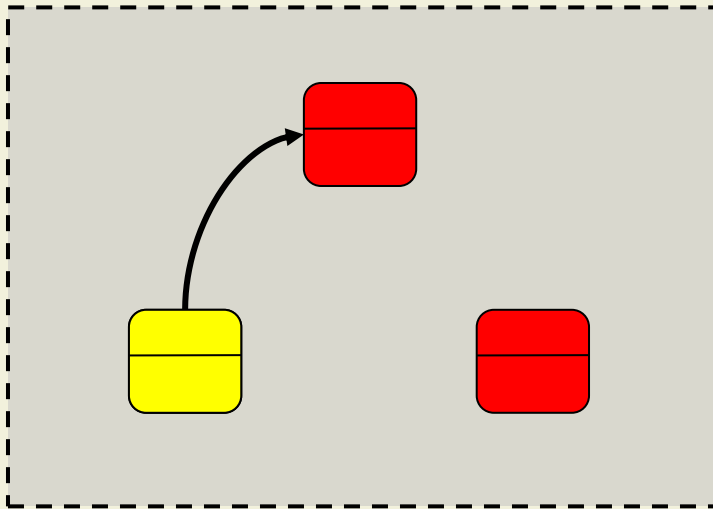
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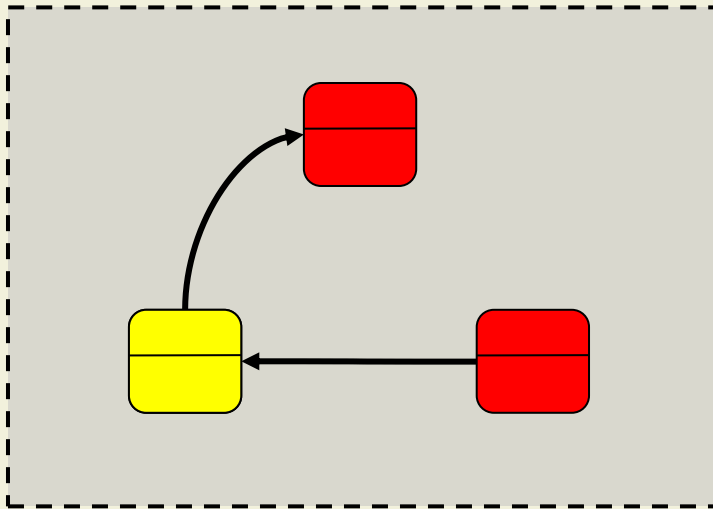
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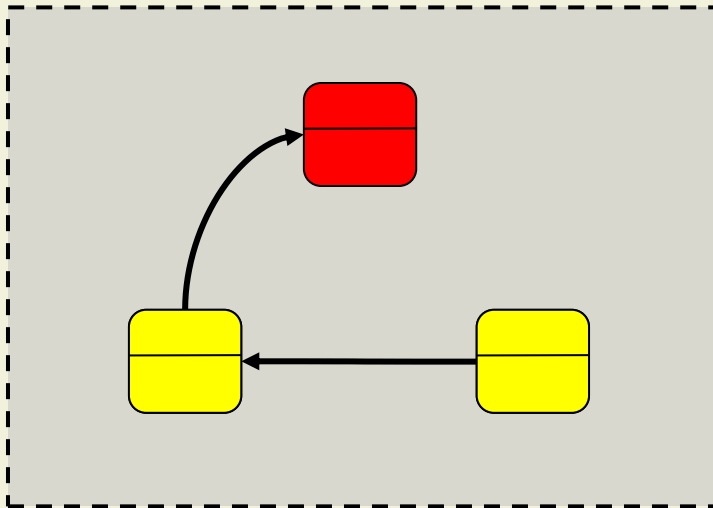
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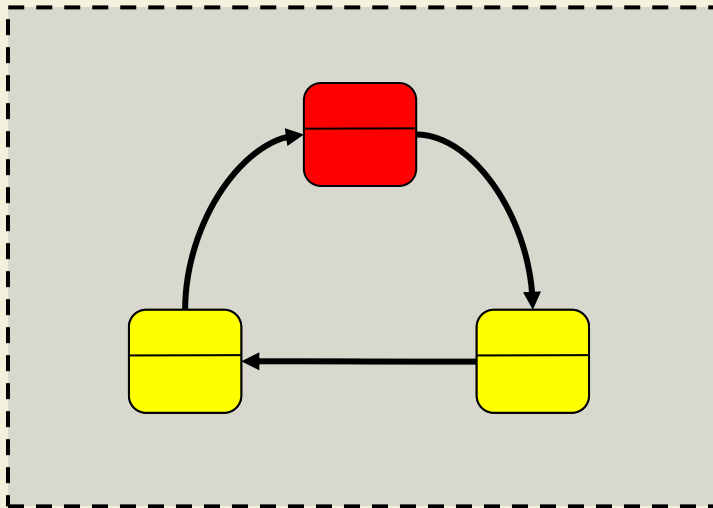
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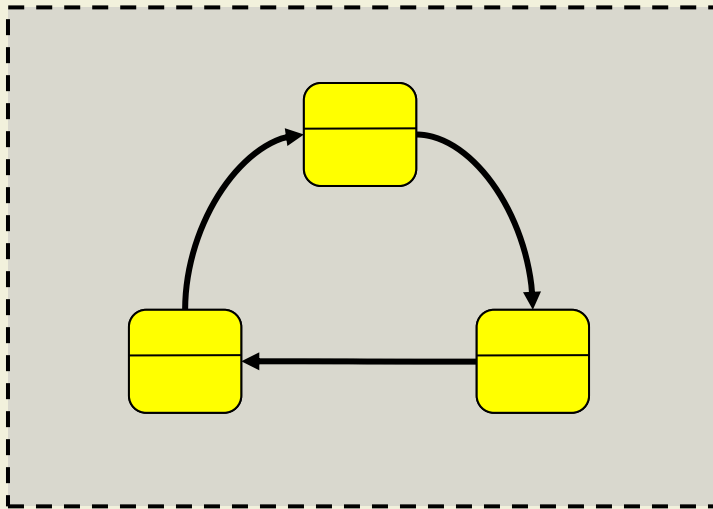
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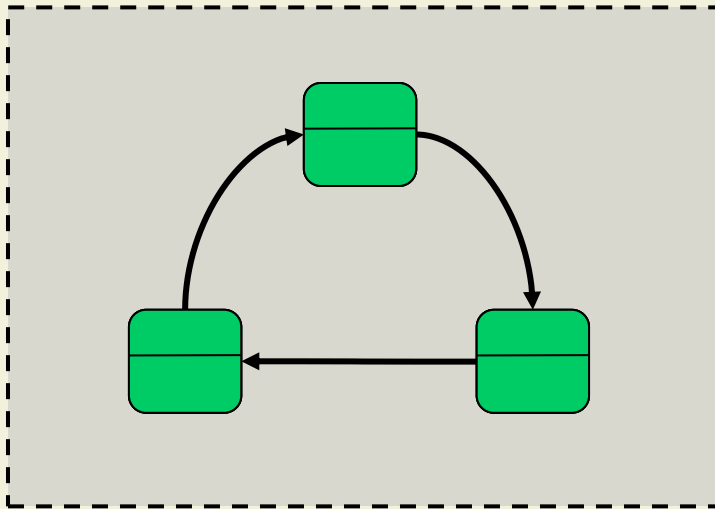
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Problem 1: Method Calls Revisited

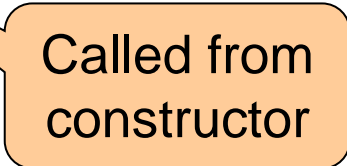
```
class Demo {  
    Vector! cache;  
  
    Demo( ) {  
        int size = optimalSize( );  
        cache = new Vector( size );  
    }  
  
    int optimalSize( ) {  
        return 16;  
    }  
}
```

```
class Sub extends Demo {  
    Vector! data;  
  
    Sub( Vector! d ) {  
        data = d.clone( );  
    }  
  
    int optimalSize( ) {  
        return this.data.size( ) * 2;  
    }  
}
```

```
Vector! v = new Vector( );  
Sub! s = new Sub( v );
```


Problem 1: Method Calls Revisited

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    Vector! cache;  
  
    Demo( ) {  
        int size = optimalSize( );  
        cache = new Vector( size );  
    }  
  
    int free optimalSize( ) {  
        return 16;  
    }  
}
```



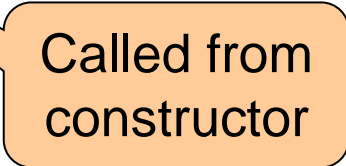
Called from constructor

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```

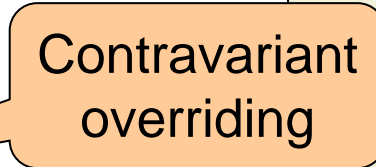
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Sub! s = new Sub( v );
```

Problem 1: Method Calls Revisited

```
class Demo {  
    Vector! cache;  
  
    Demo( ) {  
        int size = optimalSize( );  
        cache = new Vector( size );  
    }  
  
    int free optimalSize( ) {  
        return 16;  
    }  
}
```

Called from
constructor

```
class Sub extends Demo {  
    Vector! data;  
  
    Sub( Vector! d ) {  
        data = d.clone( );  
    }  
  
    int free optimalSize( ) {  
        return this.data.size( ) * 2;  
    }  
}
```

Compile-
time error

```
Vector! v = new Vector( );  
Sub! s = new Sub( v );
```

Problem 2: Call-backs Revisited

```
class Demo implements Observer {  
    static Subject! subject;  
  
    Demo( ) {  
        subject.register( this );  
    }  
  
    void update( ... ) {}  
}
```

```
class Sub extends Demo {  
    Vector! data;  
  
    Sub( Vector! d ) { data = d.clone( ); }  
    void update( ... )  
    { ... this.data.size( ) ... }  
}
```

```
class Subject {  
    void register( Observer! o ) {  
        ...  
        o.update( ... );  
    }  
}
```

```
Vector! v = new Vector( );  
Sub! s = new Sub( v );
```

Problem 2: Call-backs Revisited

```
class Demo implements Observer {  
    static Subject! subject;  
  
    Demo( ) {  
        subject.register( this );  
    }  
  
    void update( ... ) {}  
}
```

```
class Sub extends Demo {  
    Vector! data;  
  
    Sub( Vector! d ) { data = d.clone( ); }  
    void update( ... )  
    { ... this.data.size( ) ... }  
}
```

```
class Subject {  
    void register( Observer! o ) {  
        ...  
        o.update( ... );  
    }  
}
```

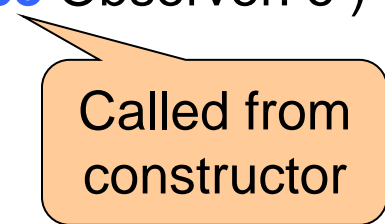
```
Vector! v = new Vector( );  
Sub! s = new Sub( v );
```

Problem 2: Call-backs Revisited

```
class Demo implements Observer {  
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        subject.register( this );  
    }  
  
    void update( ... ) {}  
}
```

```
class Sub extends Demo {  
    Vector! data;  
  
    Sub( Vector! d ) { data = d.clone( ); }  
    void update( ... )  
    { ... this.data.size( ) ... }  
}
```

```
class Subject {  
    void register( free Observer! o ) {  
        ...  
        o.update( ... );  
    }  
}
```



Called from constructor

```
Vector! v = new Vector( );  
Sub! s = new Sub( v );
```

Problem 2: Call-backs Revisited

```
class Demo implements Observer {  
    static Subject! subject;  
  
    Demo( ) {  
        subject.register( this );  
    }  
  
    void update( ... ) {}  
}
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```
class Sub extends Demo {  
    Vector! data;  
  
    Sub( Vector! d ) { data = d.clone( ); }  
    void update( ... )  
    { ... this.data.size( ) ... }  
}
```

```
class Subject {  
    void register( free Observer! o ) {  
        ...  
        o.update( ... );  
    }  
}
```

```
Vector! v = new Vector( );  
Sub! s = new Sub( v );
```

Problem 2: Call-backs Revisited

```
class Demo implements Observer {
    static Subject! subject;

    Demo( ) {
        subject.register( this );
    }

    void free update( ... ) { }
}
```

Called on free
reference

```
class Subject {
    void register( free Observer! o ) {
        ...
        o.update( ... );
    }
}
```

```
class Sub extends Demo {
    Vector! data;

    Sub( Vector! d ) { data = d.clone( ); }
    void update( ... )
    { ... this.data.size( ) ... }
}
```

```
Vector! v = new Vector( );
Sub! s = new Sub( v );
```


Problem 2: Call-backs Revisited

```
class Demo implements Observer {
  static Subject! subject;

  Demo( ) {
    subject.register( this );
  }

  void free update( ... ) { }
}
```

Called on free
reference

```
class Subject {
  void register( free Observer! o ) {
    ...
    o.update( ... );
  }
}
```

```
class Sub extends Demo {
  Vector! data;

  Sub( Vector! d ) { data = d.clone( ); }

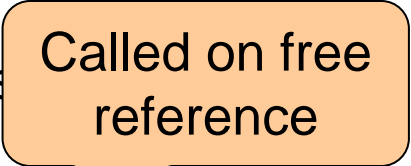
  void free update( ... )
  { ... this.data.size( ) ... }
```

Contravariant
overriding

```
Vector! v = new Vector( );
Sub! s = new Sub( v );
```

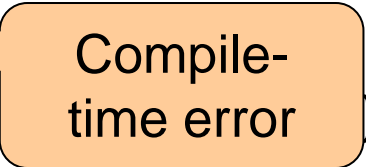
Problem 2: Call-backs Revisited

```
class Demo implements Observer {  
    static Subject! subject;  
  
    Demo( ) {  
        subject.register( this );  
    }  
  
    void free update( ... ) { }  
}
```



Called on free reference

```
class Sub extends Demo {  
    Vector! data;  
  
    Sub( Vector! d ) { data = d.clone( ); }  
    void free update(  
        { ... this.data.size( ) }  
    }
```



Compile-time error

```
class Subject {  
    void register( free Observer! o ) {  
        ...  
        o.update( ... );  
    }  
}
```

```
Vector! v = new Vector( );  
Sub! s = new Sub( v );
```

Problem 3: Escaping via Calls Revisited

```
class Demo implements Observer {  
    static Subject! subject;  
  
    Demo( ) {  
        subject.register( this );  
    }  
  
    void update( ... ) { }  
}
```

```
class Sub extends Demo {  
    Vector! data;  
  
    Sub( Vector! d ) { data = d.clone( ); }  
    void update( ... ) { ... data.size( ) ... }  
}
```

```
class Subject extends Thread {  
    List<Observer!>! list;  
  
    void register( Observer! o )  
    { list.add( o ); }  
  
    void run( ) {  
        while( true ) {  
            if( sensorValueChanged( ) )  
                for( Observer! o: list )  
                    o.update( ... );  
        }  
    }  
    ...  
}
```

Problem 3: Escaping via Calls Revisited

```
class Demo implements Observer {  
    static Subject! subject;  
  
    Demo( ) {  
        subject.register( this );  
    }  
  
    void update( ... ) { }  
}
```

```
class Sub extends Demo {  
    Vector! data;  
  
    Sub( Vector! d ) { data = d.clone( ); }  
    void update( ... ) { ... data.size( ) ... }  
}
```

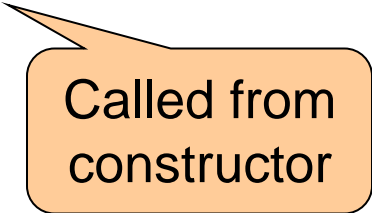
```
class Subject extends Thread {  
    List<Observer!>! list;  
  
    void register( Observer! o )  
    { list.add( o ); }  
  
    void run( ) {  
        while( true ) {  
            if( sensorValueChanged( ) )  
                for( Observer! o: list )  
                    o.update( ... );  
        }  
    }  
    ...  
}
```

Problem 3: Escaping via Calls Revisited

```
class Demo implements Observer {  
    static Subject! subject;  
  
    Demo( ) {  
        subject.register( this );  
    }  
  
    void update( ... ) { }  
}
```

```
class Sub extends Demo {  
    Vector! data;  
  
    Sub( Vector! d ) { data = d.clone( ); }  
    void update( ... ) { ... data.size( ) ... }  
}
```

```
class Subject extends Thread {  
    List<Observer!>! list;  
  
    void register( free Observer! o )  
    { list.add( o ); }  
  
    void run( ) {  
        while( true ) {  
            if( sensorValueChanged( ) )  
                for( Observer! o: list )  
                    o.update( ... );  
        }  
    }  
    ...  
}
```



Called from constructor

Problem 3: Escaping via Calls Revisited

```
class Demo implements Observer {
    static Subject! subject;

    Demo( ) {
        subject.register( this );
    }

    void update( ... ) { }
}
```

```
class Sub extends Demo {
    Vector! data;

    Sub( Vector! d ) { data = d.clone( ); }
    void update( ... ) { ... data.size( ) ... }
}
```

```
class Subject extends Thread {
    List<Observer!>! list;

    void register( free Observer! o )
    { list.add( o ); }

    void run( ) {
        while( true
            if( sensor( ... ) )
                for( Observer! o: list )
                    o.update( ... );
        }
    }
    ...
}
```

add requires committed argument

Problem 4: Escaping via Fields Revisited

```
class Node {  
    Node! next; // a cyclic list  
    Process! proc;  
  
    Node( Node! after, Process! p ) {  
        this.next = after.next;  
        after.next = this;  
        proc = p;  
    }  
}
```

```
class Scheduler extends Thread {  
    Node! current;  
  
    void run( ) {  
        while( true ) {  
            current.proc.preempt( );  
            current = current.next;  
            current.proc.resume( );  
            Thread.sleep( 1000 );  
        }  
    }  
    ...  
}
```

Problem 4: Escaping via Fields Revisited

```
class Node {  
    Node! next; // a cyclic list  
    Process! proc;  
  
    Node( Node! after, Process! p ) {  
        this.next = after.next;  
        after.next = this;  
        proc = p;  
    }  
}
```

New node cannot
be inserted before
construction is
complete

```
class Scheduler extends Thread {  
    Node! current;  
  
    void run( ) {  
        while( true ) {  
            current.proc.preempt( );  
            current = current.next;  
            current.proc.resume( );  
            Thread.sleep( 1000 );  
        }  
    }  
    ...  
}
```


Lazy Initialization

- Creating objects and initializing their fields is time consuming
 - Long application start-up time
- Lazy initialization: initialize fields when they are first used
 - Spreads initialization effort over longer time period

```
class Demo {  
    private Vector? data;  
  
    Demo( ) {  
        // do not initialize data  
    }  
  
    public Vector! getData( ) {  
        Vector? d = data;  
        if( d == null ) {  
            d = new Vector( ); data = d;  
        }  
        return d;  
    }  
}
```

Lazy Initialization

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 - Long application start-up time
- Lazy initialization: initialize fields when they are first used
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Not initialized by constructor

```
class Demo {  
    private Vector? data;  
  
    Demo( ) {  
        // do not initialize data  
    }  
  
    public Vector! getData( ) {  
        Vector? d = data;  
        if( d == null ) {  
            d = new Vector( ); data = d;  
        }  
        return d;  
    }  
}
```

Lazy Initialization

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```
class Demo {  
    private Vector? data;  
  
    Demo() {  
        // do not init  
    }  
  
    public Vector! getData() {  
        Vector? d = data;  
        if( d == null ) {  
            d = new Vector(); data = d;  
        }  
        return d;  
    }  
}
```

Not initialized
by constructor

Clients get non-
null guarantee

Non-Null Arrays

- Arrays are objects whose fields are numbered
- An array type describes two kinds of references
 - The reference to the array object
 - The references to the array elements
 - Both can be non-null or possibly-null

Non-Null Arrays

- Arrays are objects whose fields are numbered
- An array type describes two kinds of references
 - The reference to the array object
 - The references to the array elements
 - Both can be non-null or possibly-null

```
Person! [ ] ! a;  
Person? [ ] ! b;  
Person! [ ] ? c;  
Person? [ ] ? d;
```

Non-Null Arrays

- Arrays are objects whose fields are numbered
- An array type describes two kinds of references
 - The reference to the array object
 - The references to the array elements
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Non-null array with
non-null elements

```
Person! [ ] ! a;  
Person? [ ] ! b;  
Person! [ ] ? c;  
Person? [ ] ? d;
```

Non-Null Arrays

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Non-null array with
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Non-null array with
possibly-null
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Non-Null Arrays

- Arrays are objects whose fields are numbered
- An array type describes two kinds of references
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 - The references to the array elements
 - Both can be non-null or possibly-null

Non-null array with
non-null elements

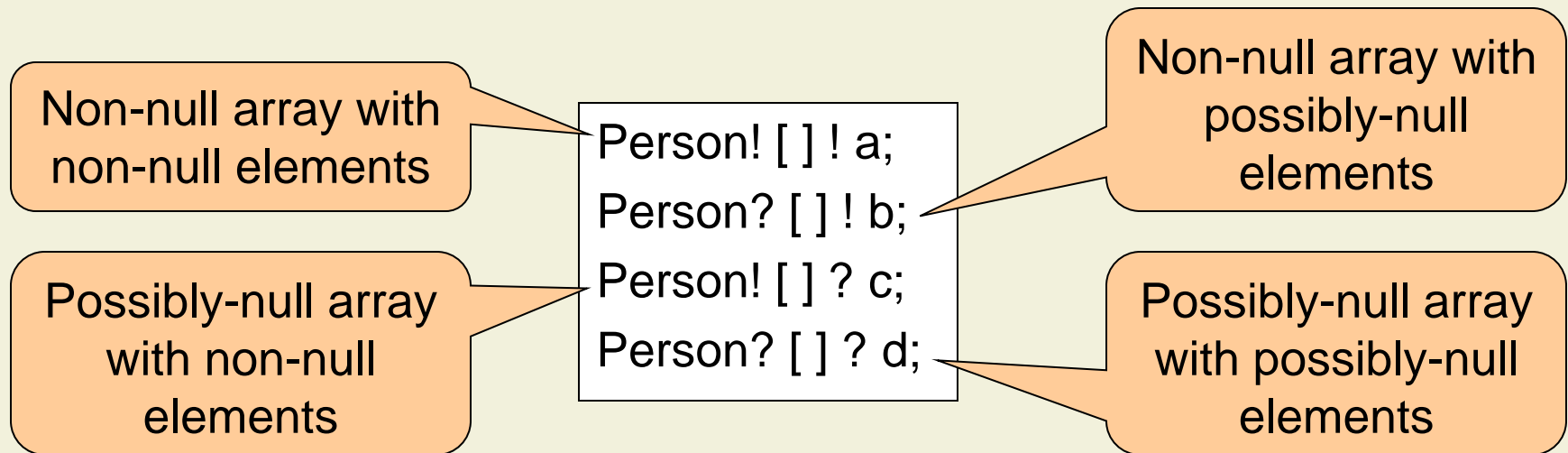
Possibly-null array
with non-null
elements

```
Person! [ ] ! a;  
Person? [ ] ! b;  
Person! [ ] ? c;  
Person? [ ] ? d;
```

Non-null array with
possibly-null
elements

Non-Null Arrays

- Arrays are objects whose fields are numbered
- An array type describes two kinds of references
 - The reference to the array object
 - The references to the array elements
 - Both can be non-null or possibly-null



Problems of Array Initialization

- Our solution for non-null fields does not work for non-null array elements
 - No constructor for arrays
 - Arrays are typically initialized using loops
 - Static analyses ignore loop conditions
- In general, definite assignment cannot be checked by compiler

```
class Demo {  
    String! [ ] ! s;  
  
    Demo( int l ) {  
        if( l % 2 == 1 )  
            l = l + 1;  
        s = new String! [ l ];  
  
        for( int i = 0; i < l / 2; i++ ) {  
            s[ i*2 ] = "Even";  
            s[ i*2 + 1 ] = "Odd";  
        }  
    }  
}
```

Problems of Array Initialization

- Our solution for non-null fields does not work for non-null array elements
 - No constructor for arrays
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class Demo {  
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    Demo( int l ) {  
        if( l % 2 == 1 )  
            l = l + 1;  
        s = new String! [ l ];  
  
        for( int i = 0; i < l / 2; i++ ) {  
            s[ i*2 ] = "Even";  
            s[ i*2 + 1 ] = "Odd";  
        }  
    }  
}
```

When do the elements have to contain non-null references?

Problems of Array Initialization

- Our solution for non-null fields does not work for non-null array elements
 - No constructor for arrays
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    Demo( int l ) {  
        if( l % 2 == 1 )  
            l = l + 1;  
        s = new String! [ l ];  
  
        for( int i = 0; i < l / 2; i++ ) {  
            s[ i*2 ] = "Even";  
            s[ i*2 + 1 ] = "Odd";  
        }  
    }  
}
```

When do the elements have to contain non-null references?

Are all elements of s initialized?

Array Initialization: (Partial) Solutions

- Array initializers

```
String! [ ] ! s = { “array”, “of”, “non-null”, “String” };
```

Array Initialization: (Partial) Solutions

- Array initializers

```
String! [ ] ! s = { "array", "of", "non-null", "String" };
```

- Pre-filling the array

```
my_array: attached ARRAY [ attached STRING ]  
create my_array.make_filled ( " ", 1, 1 )
```

Eiffel

- Not clear why a default object is any better than **null**

Array Initialization: (Partial) Solutions

- Array initializers

```
String! [ ] ! s = { "array", "of", "non-null", "String" };
```

- Pre-filling the array

```
my_array: attached ARRAY [ attached STRING ]  
create my_array.make_filled ( " ", 1, l )
```

Eiffel

- Not clear why a default object is any better than **null**

- Run-time checks

```
String! [ ] ! s = new String! [ l ];  
for( int i = 0; i < l / 2; i++ ) { /* as before */ }  
NonNullType.AssertInitialized( s );
```

Spec#

Array Initialization: (Partial) Solutions

- Array initializers

```
String! [ ] ! s = { "array", "of", "non-null", "String" };
```

- Pre-filling the array

```
my_array: attached ARRAY [ attached STRING ]  
create my_array.make_filled ( " ", 1, l )
```

Eiffel

- Not clear why a default object is any better than **null**

- Run-time checks

```
String! [ ] ! s = new String! [ l ];  
for( int i = 0; i < l / 2; i++ ) { /* as before */  
  NonNullType.AssertInitialized( s );
```

Changes type from
free to committed

Spec#

Summary

- Object initialization has to establish invariants
 - Non-nullness of fields is just an example
- General guidelines for writing constructors
 - Avoid calling dynamically-bound methods on **this**
 - Be careful when new object escapes from constructor
 - Be aware of subclass constructors that have not run yet
- Non-null types are available in Spec#
 - specsharp.codeplex.com

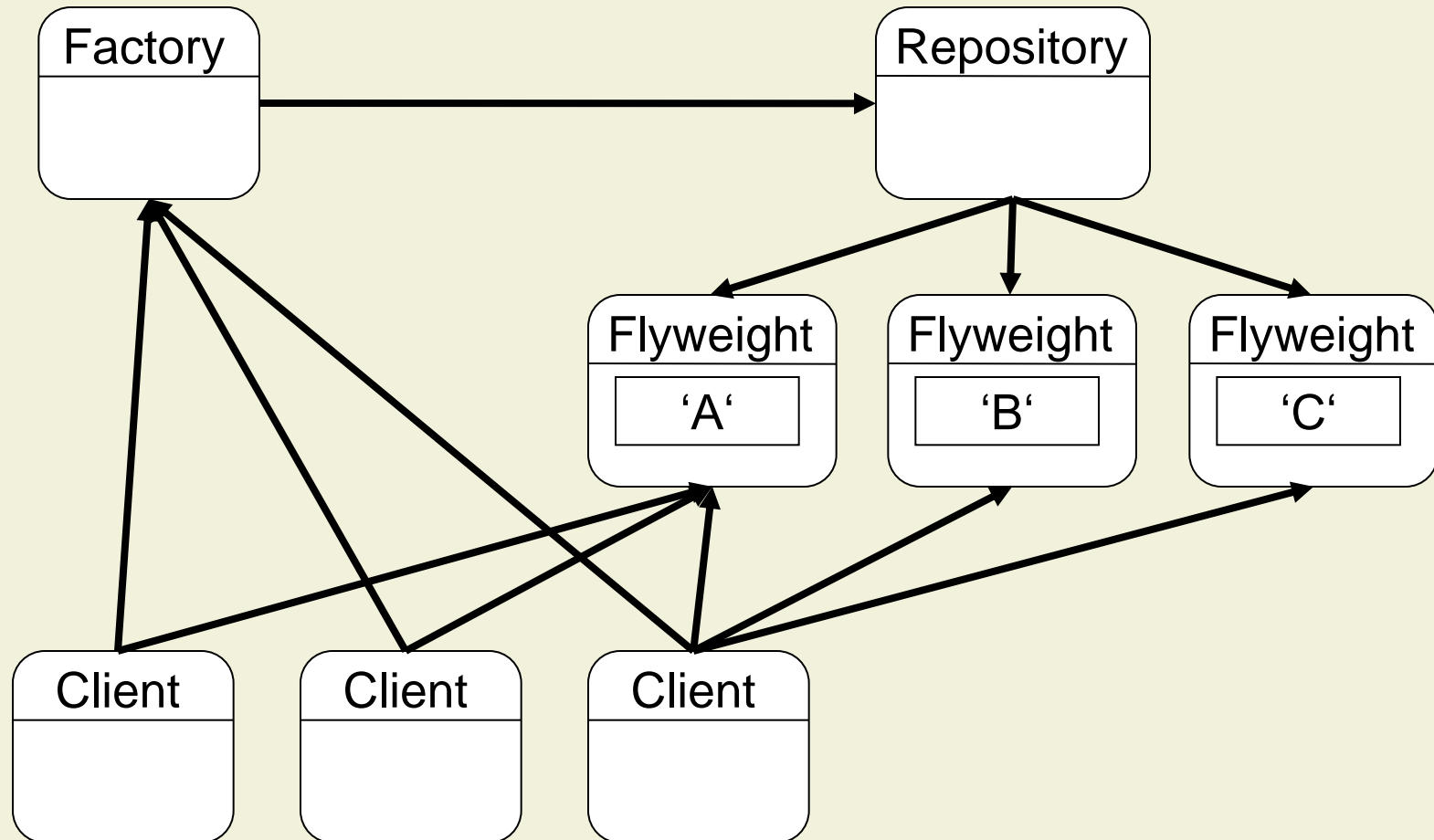
8. Initialization

8.1 Simple Non-Null Types

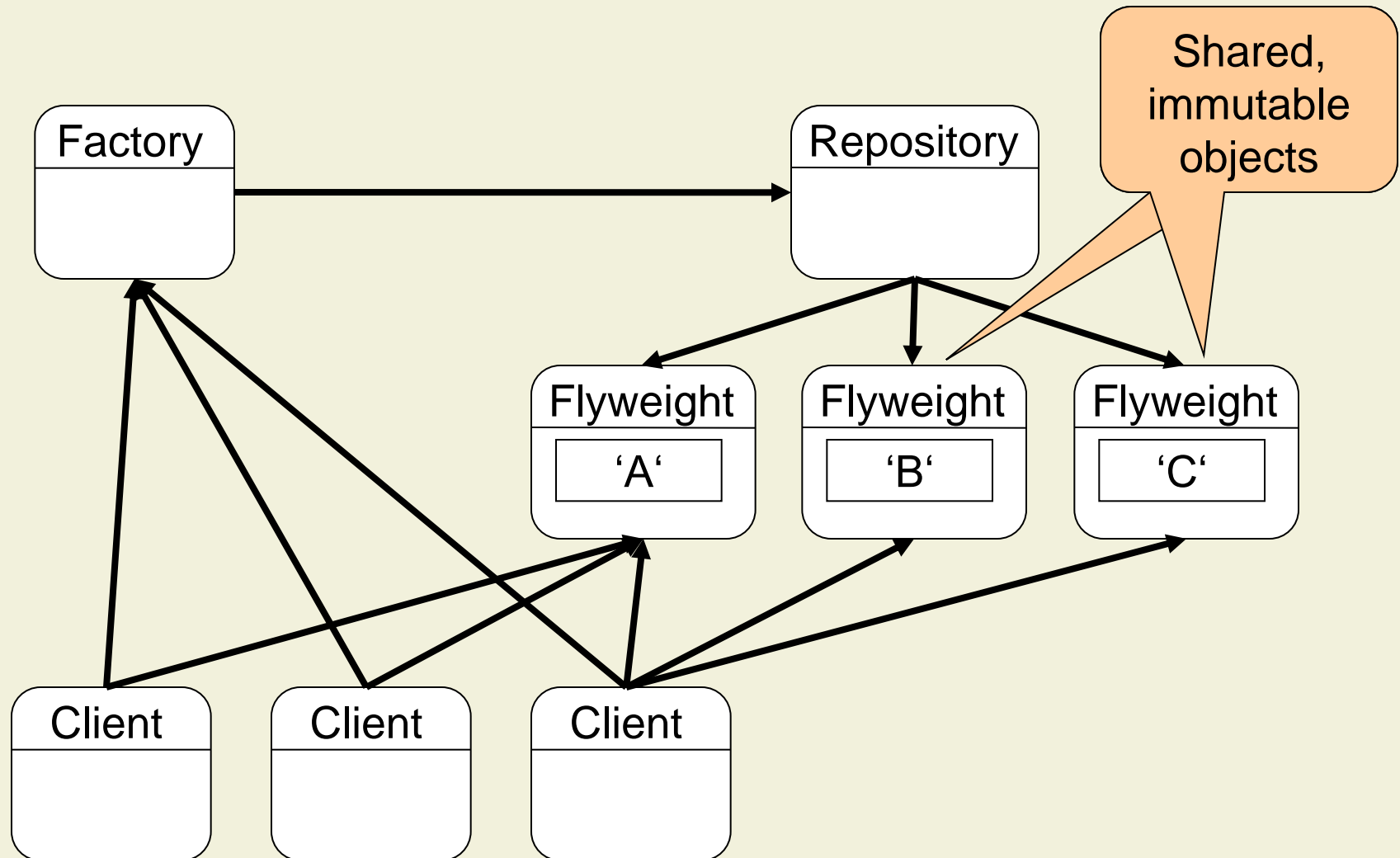
8.2 Object Initialization

8.3 Initialization of Global Data

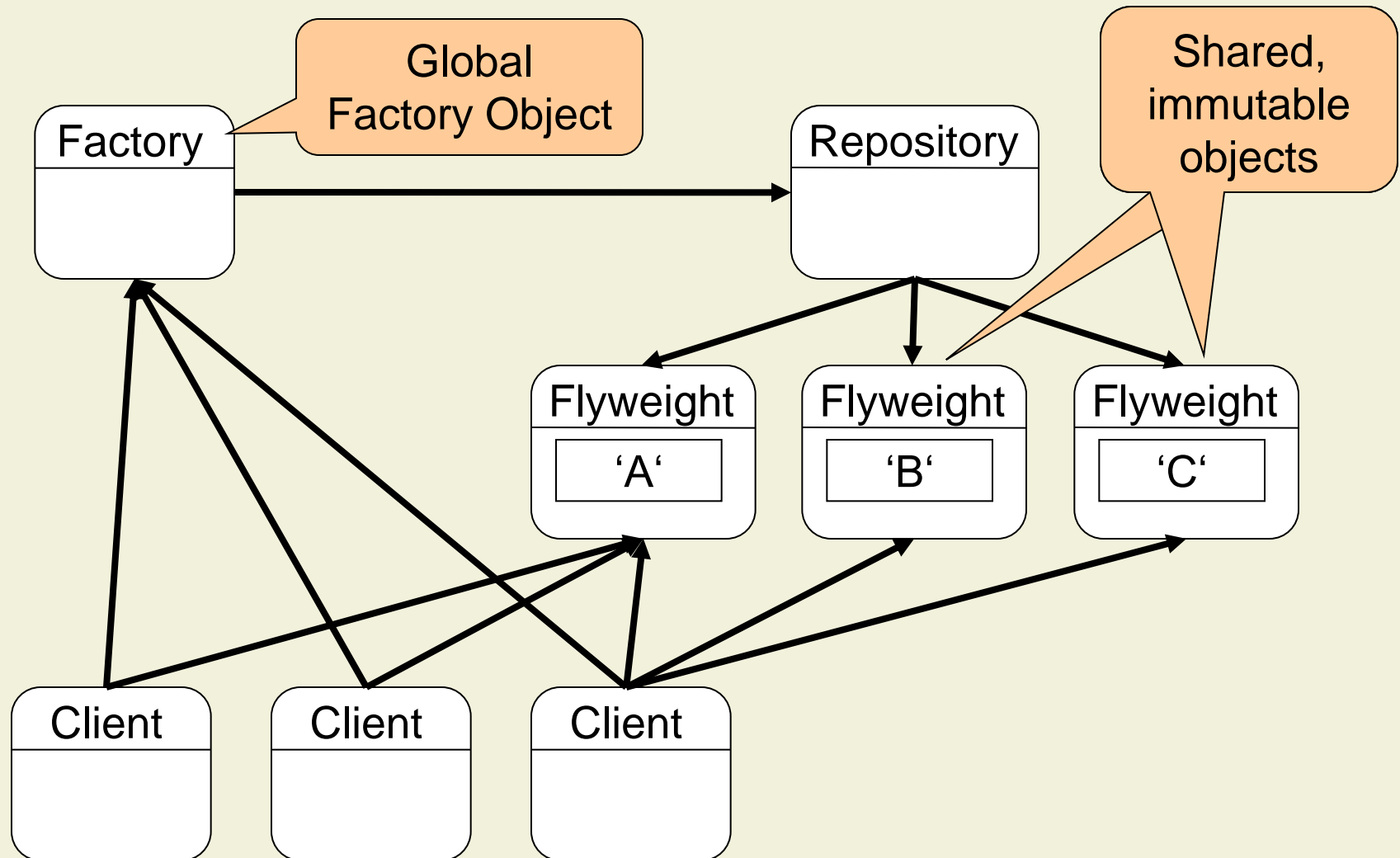
The Flyweight Pattern



The Flyweight Pattern

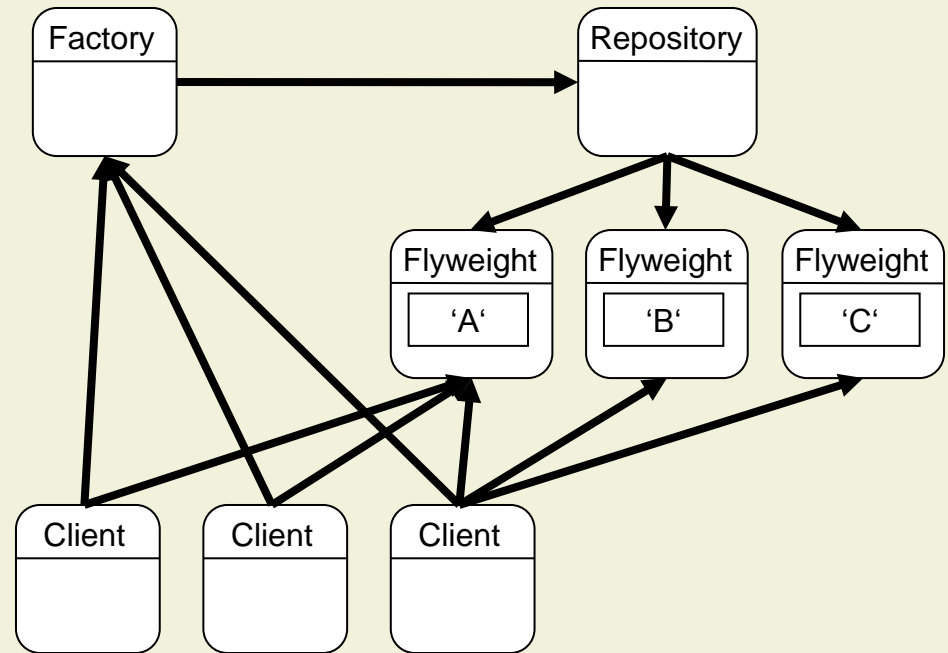


The Flyweight Pattern



Global Data

- Most software systems maintain global data
 - Factories
 - Caches
 - Flyweights
 - Singletons
- Main issues
 - How do clients access the global data?
 - How is the global data initialized?



Initialization of Globals: Design Goals

- Effectiveness
 - Ensure that global data is **initialized before first access**
 - Example: non-nullness
- Clarity
 - Initialization has a **clean semantics** and facilitates reasoning
- Laziness
 - Global data is **initialized lazily** to reduce start-up time

Solution 1: Global Vars and Init-Methods

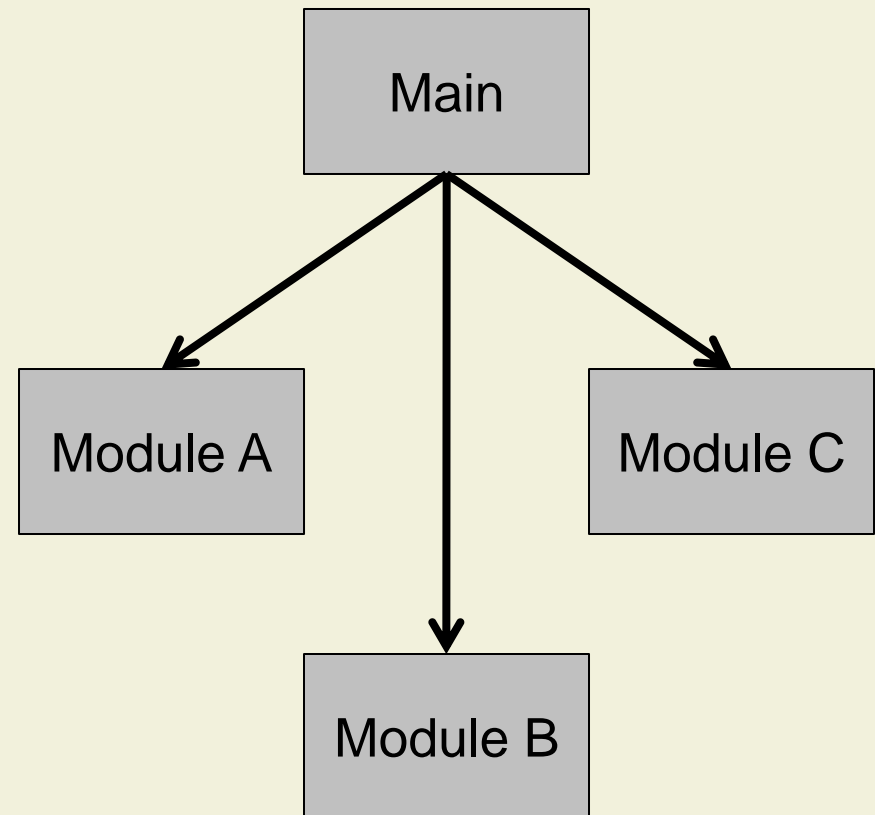
- **Global variables**
store references to
global data
- Initialization is done
by **explicit calls** to
init-methods

```
global Factory theFactory;  
  
void init( ) {  
    theFactory = new Factory( );  
}  
  
class Factory {  
    HashMap flyweights;  
  
    Flyweight create( Data d ) { ... }  
    ...  
}
```

```
Flyweight f = theFactory.create( ... );
```

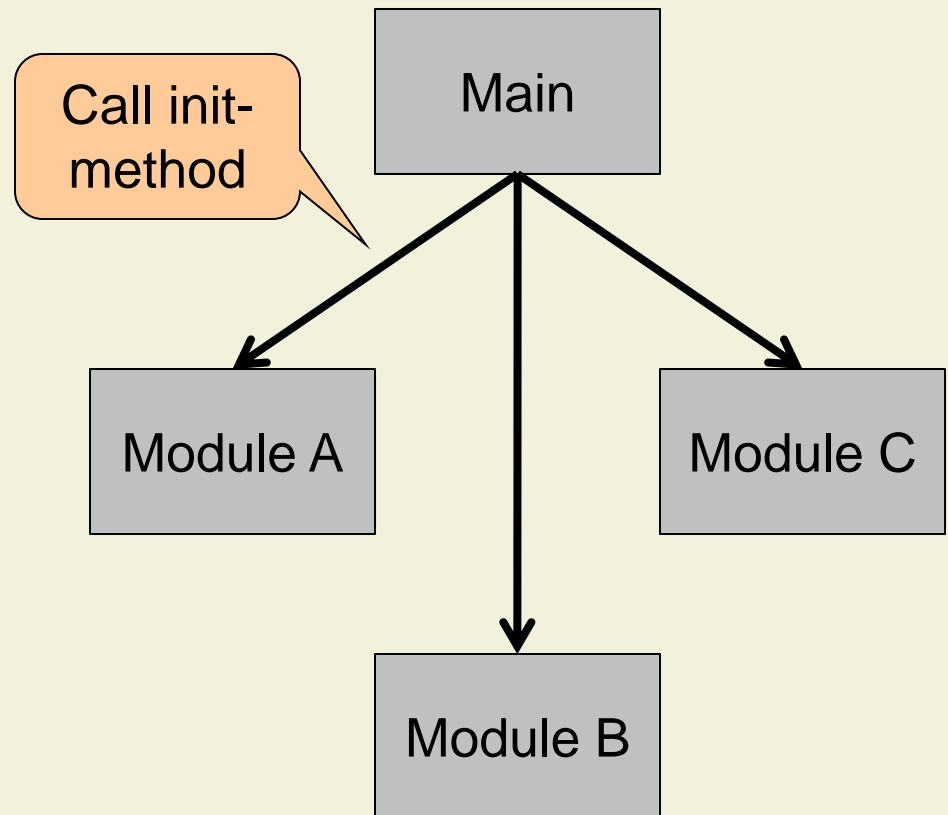

Globals and Init-Methods: Dependencies

- Init-methods are called directly or indirectly from main-method
- To ensure effective initialization, main **needs to know internal dependencies** of modules



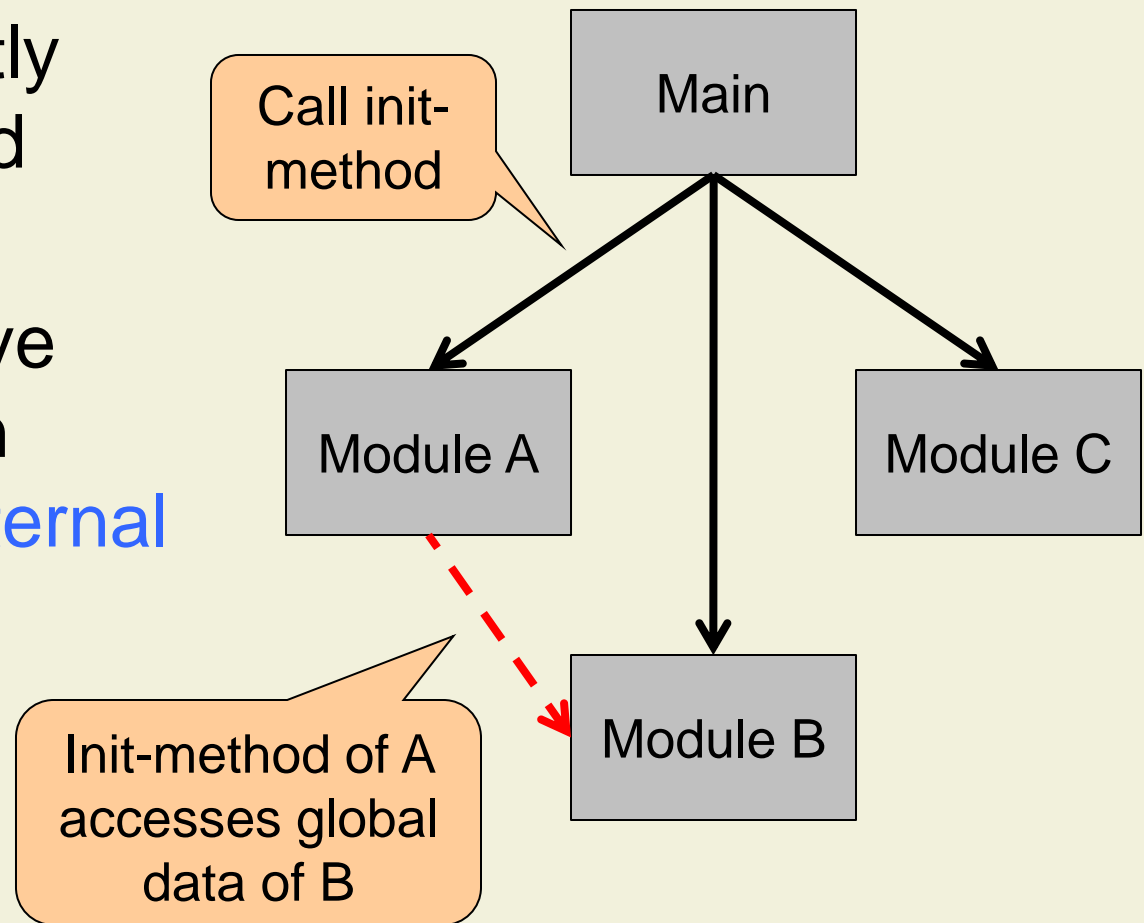
Globals and Init-Methods: Dependencies

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Globals and Init-Methods: Dependencies

- Init-methods are called directly or indirectly from main-method
- To ensure effective initialization, main needs to know internal dependencies of modules



Globals and Init-Methods: Summary

- Effectiveness
 - Initialization order needs to be **coded manually**
 - Error-prone
- Clarity
 - Dependency information **compromises information hiding**
- Laziness
 - Needs to be **coded manually**

Variation: C++ Initializers

- Global variables can have initializers
- Initializers are executed before execution of main-method
 - No explicit calls needed
 - No support for lazy initialization
- Order of execution determined by order of appearance in the source code
 - Programmer has to manage dependencies

```
class Factory {  
    HashMap* flyweights;  
  
    Flyweight* create( Data* d ) { ... }  
  
    ...  
};  
  
Factory* theFactory = new Factory( );
```

C++

Solution 2: Static Fields and Initializers

- **Static fields** store references to global data
- Static initializers are executed by the system **immediately before a class is used**

```
class Factory {  
    static Factory theFactory;  
    HashMap flyweights;  
  
    static {  
        theFactory = new Factory( );  
    }  
  
    Flyweight create( Data d ) { ... }  
    ...  
}
```

Java

```
Factory o = Factory.theFactory;  
Flyweight f = o.create( ... );
```

Execution of Static Initializers

- A class C's static initializer runs **immediately before first**
 - Creation of a C-instance
 - Call to a static method of C
 - Access to a static field of Cand before static initializers of C's subclasses
- Initialization is done **lazily**
- System manages dependencies

```
class Factory {  
    static Factory theFactory;  
    HashMap flyweights;  
  
    static {  
        theFactory = new Factory( );  
    }  
  
    Flyweight create( Data d ) { ... }  
    ...  
}
```

Java

```
Factory o = Factory.theFactory;  
Flyweight f = o.create( ... );
```

Execution of Static Initializers

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 - Call to a static method of C
 - Access to a static field of Cand before static initializers of C's subclasses
- Initialization is done **lazily**
- System manages dependencies

```
class Factory {  
    static Factory theFactory;  
    HashMap flyweights;  
  
    static {  
        theFactory = new Factory( );  
    }  
  
    Flyweight create( Data d ) { ... }  
  
    ...  
}
```

Initialization triggered here

Java

```
Factory o = Factory.theFactory;  
Flyweight f = o.create( ... );
```


Static Initializers: Mutual Dependencies

```
class Debug {  
    static int session;  
    static Vector logfile;  
  
    static {  
        session = UniqueID.getID( );  
        logfile = new Vector( );  
    }  
  
    static void log( String msg ) {  
        logfile.add( msg );  
    }  
}
```

```
class UniqueID {  
    static int next;  
  
    static {  
        next = 1;  
        Debug.log( “...” );  
    }  
  
    static int getID( ) {  
        return next++;  
    }  
}
```

```
Debug.log( “Start of program execution” );
```

Java

Static Initializers: Mutual Dependencies

```
class Debug {  
    static int session;  
    static Vector logfile;  
  
    static {  
        session = UniqueID.getID( );  
        logfile = new Vector( );  
    }  
  
    static void log( String msg ) {  
        logfile.add( msg );  
    }  
}
```

Initialize
Debug

```
class UniqueID {  
    static int next;  
  
    static {  
        next = 1;  
        Debug.log( “...” );  
    }  
  
    static int getID( ) {  
        return next++;  
    }  
}
```

```
Debug.log( “Start of program execution” );
```

Java

Static Initializers: Mutual Dependencies

```
class Debug {  
    static int session;  
    static Vector logfile;  
  
    static {  
        session = UniqueID.getID( );  
        logfile = new Vector( );  
    }  
  
    static void log( String msg ) {  
        logfile.add( msg );  
    }  
}
```

Initialize
UniqueID

Initialize
Debug

```
class UniqueID {  
    static int next;  
  
    static {  
        next = 1;  
        Debug.log( “...” );  
    }  
  
    static int getID( ) {  
        return next++;  
    }  
}
```

```
Debug.log( “Start of program execution” );
```

Java

Static Initializers: Mutual Dependencies

```
class Debug {  
    static int session;  
    static Vector logfile;  
  
    static {  
        session = UniqueID.getID( );  
        logfile = new Vector( );  
    }  
  
    static void log( String msg ) {  
        logfile.add( msg );  
    }  
}
```

Initialize
UniqueID

Initialize
Debug

```
class UniqueID {  
    static int next;  
  
    static {  
        next = 1;  
        Debug.log( “...” );  
    }  
  
    static int getID( ) {  
        return next++;  
    }  
}
```

Initialization
already in progress

```
Debug.log( “Start of program execution” );
```

Java

Static Initializers: Mutual Dependencies

```
class Debug {  
    static int session;  
    static Vector logfile;  
  
    static {  
        session = UniqueID.getID( );  
        logfile = new Vector( );  
    }  
  
    static void log( String msg ) {  
        logfile.add( msg );  
    }  
}
```

Initialize
UniqueID

Initialize
Debug

NullPointerException

```
class UniqueID {  
    static int next;  
  
    static {  
        next = 1;  
        Debug.log( "..." );  
    }  
  
    static int getID( ) {  
        return next++;  
    }  
}
```

Initialization
already in progress

```
Debug.log( "Start of program execution" );
```

Java

Static Initializers: Side Effects

```
class C {  
    static int x;  
  
    ...  
}
```

```
class D {  
    static char y;  
  
    ...  
}
```

```
C.x = 0;  
D.y = '?';  
assert C.x == 0;
```

Static Initializers: Side Effects

- Static initializers may have **arbitrary side effects**

```
class C {  
    static int x;  
  
    ...  
}
```

```
class D {  
    static char y;  
  
    static { C.x = C.x + 1; }  
}
```

```
C.x = 0;  
D.y = '?';  
assert C.x == 0;
```

Static Initializers: Side Effects

- Static initializers may have **arbitrary side effects**
- Reasoning about programs with static initializers is **non-modular**
 - Need to know when initializers run

```
class C {  
    static int x;  
  
    ...  
}
```

```
class D {  
    static char y;  
  
    static { C.x = C.x + 1; }  
}
```

```
C.x = 0;  
D.y = '?';  
assert C.x == 0;
```


Static Initializers: Summary

- Effectiveness

- Static initializers may be **interrupted**
- **Reading un-initialized fields** is possible

- Clarity

- Reasoning requires to **keep track** of which initializers have run already
- **Side effects through implicit executions** of static initializers can be surprising

- Laziness

- Static initializers are not called upfront (but also not as late as possible)

Static Fields and Procedural Style

- Procedural style: make all fields and operations of the global data static
 - Use class object as global object
- Disadvantages
 - No specialization via subtyping and overriding
 - No dynamic exchange of data structure
 - Not object-oriented

```
class Factory {  
    static HashMap flyweights;  
  
    static {  
        flyweights = new HashMap( );  
    }  
  
    static  
    Flyweight create( Data d ) {  
        ...  
    }  
    ...  
}
```

Java

Variation: Scala's Singleton Objects

- Scala provides language support for **singletons**
 - Singleton objects may extend classes or traits
 - But they **cannot be specialized**
- Not every global object is a singleton
- Initialization is **defined by translation to Java**
 - Inherits all pros and cons of static initializers

```
object Factory {  
  val flyweights: HashMap[ ... ]  
  
  def  
  create( d: Data ): Flyweight =  
    ...  
  ...  
}
```

Scala

Solution 3: Eiffel's Once Methods

- Once methods are **executed only once**
- **Result** of first execution **is cached** and returned for subsequent calls

```
class FlyweightMgr
feature
  theFactory: Factory
  once
    create Result
  end
  ...
end
```

Eiffel

```
o := manager.theFactory
f := o.createFlyweight( ... )
```

Once Methods: Mutual Dependencies

- Mutual dependencies lead to recursive calls
- Recursive calls return the **current value of Result**
 - Typically not a meaningful value

```
factorial ( i: INTEGER ): INTEGER
  require 0 <= i
  once
    if i <= 1 then Result := 1
    else
      Result := i * factorial ( i - 1 )
    end
  end
```

Eiffel

```
check factorial( 3 ) = 0 end
check factorial( 30 ) = 0 end
```

Once Methods: Parameters

- Arguments to once methods are used for the first execution
- Arguments to subsequent calls are ignored

```
factorial ( i: INTEGER ): INTEGER
  require 0 <= i
  once
    if i <= 1 then Result := 1
    else
      Result := i * factorial ( i - 1 )
    end
  end
```

Eiffel

```
check factorial( 3 ) = 0 end
check factorial( 30 ) = 0 end
check factorial( 1 ) = 0 end
```

```
check factorial( 1 ) = 1 end
check factorial( 3 ) = 1 end
check factorial( 30 ) = 1 end
```

Once Methods: Summary

- Effectiveness
 - Mutual dependencies lead to recursive calls
 - Reading un-initialized fields is possible
- Clarity
 - Reasoning requires to keep track of which once methods have run already (use of arguments, side effects)
- Laziness
 - Once methods are executed only when result is needed (as late as possible)

Initialization of Global Data: Summary

- No solution ensures that global data is initialized before it is accessed
 - How to establish invariants over global data?
 - For instance, solutions would not be suitable to ensure that global non-null variables have non-null values

- No solution handles mutual dependencies
 - Maybe programmer should determine initialization order, with appropriate restrictions

References

- Manuel Fähndrich and K. Rustan M. Leino: *Declaring and Checking Non-Null Types in an Object-Oriented Language*. OOPSLA 2003
- Alexander J. Summers and Peter Müller: *Freedom Before Commitment – A Lightweight Type System for Object Initialisation*. OOPSLA 2011