

Concepts of Object-Oriented Programming

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Chair of Programming Methodology

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Meeting the Requirements

Cooperating Program Parts with Well-Defined Interfaces

- Objects (data + code)
- Interfaces
- Encapsulation

Classification and Specialization

- Classification, subtyping
- Polymorphism
- Substitution principle

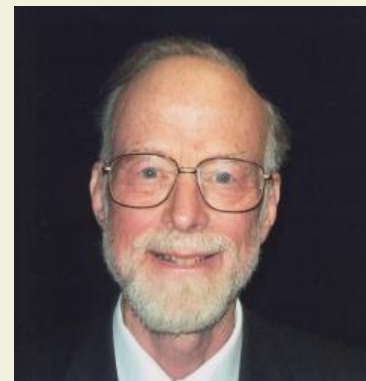
Highly Dynamic Execution Model

- 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]

7. Initialization

7.1 Simple Non-Null Types

7.2 Object Initialization

7.3 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**

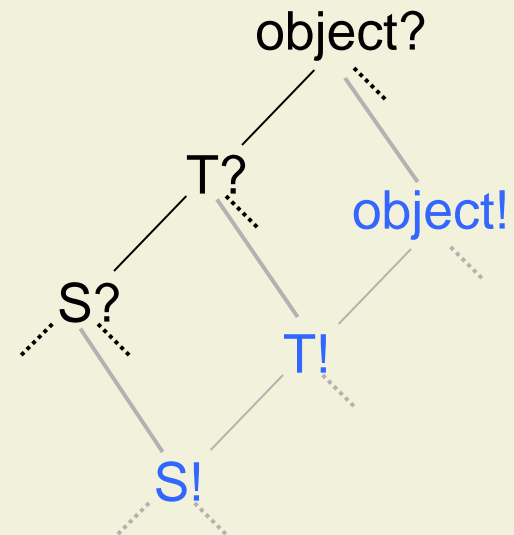
- Goal: prevent null-dereferencing statically
 - Require non-null types for the receiver of each field access, array access, method call
 - Analogous to preventing “message not understood” errors with classical type systems

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 { ... }
```

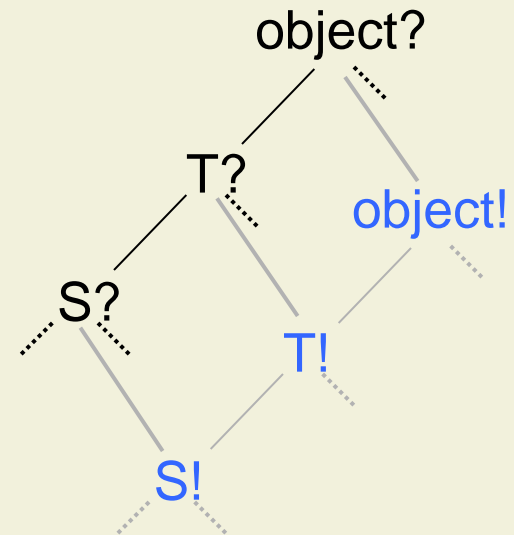


Subtyping and Casts

- 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;
```

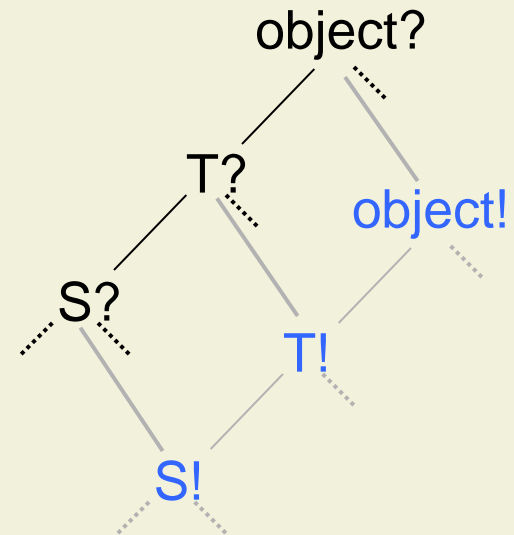
```
pnT = nnT;
```

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**

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

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



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

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

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

```
nnT = nnS;
```

```
pnT = pnS;
```

```
pnT = nnT;
```

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

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

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 ) {  
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    if( n == null ) return null;  
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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 );  
  }  
}
```

Comparing against null

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

Compile-time error:
possible
null-dereferencing

```
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]

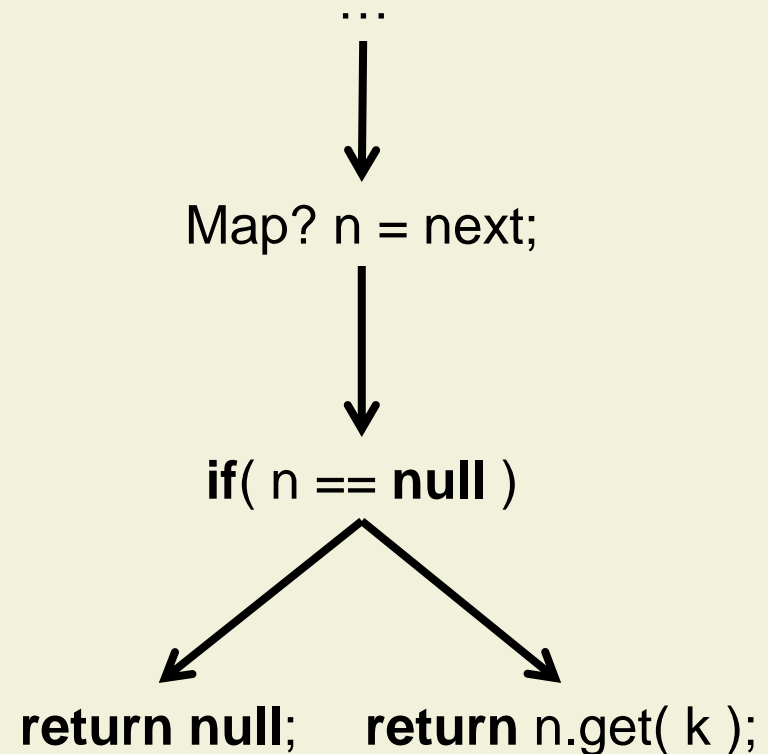
Comparing against null (cont'd)

```
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 );  
  }  
}
```

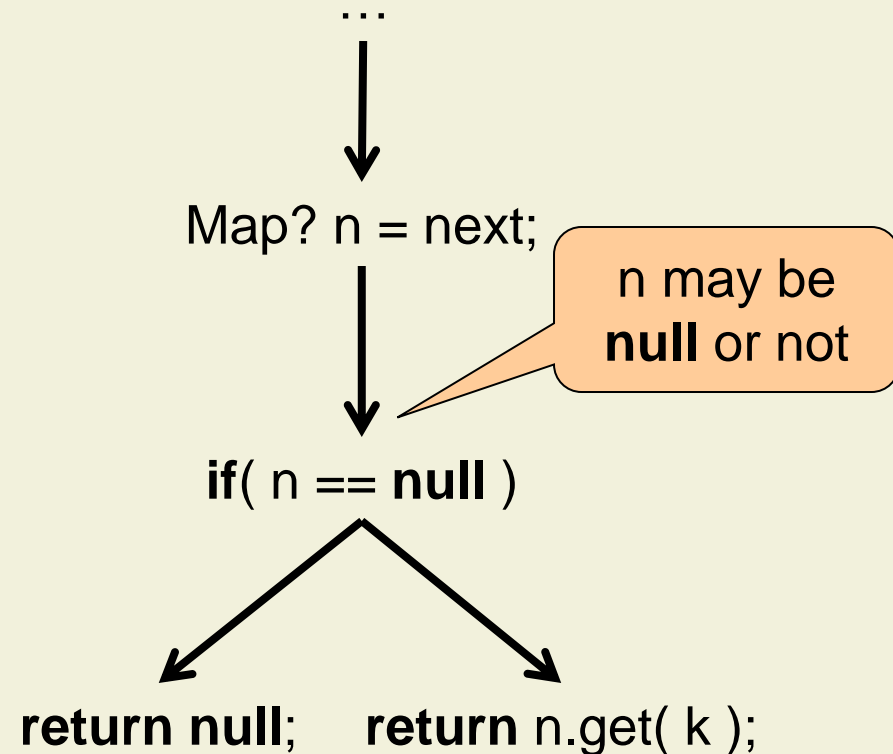
Control Flow Graph



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 );  
  }  
}
```

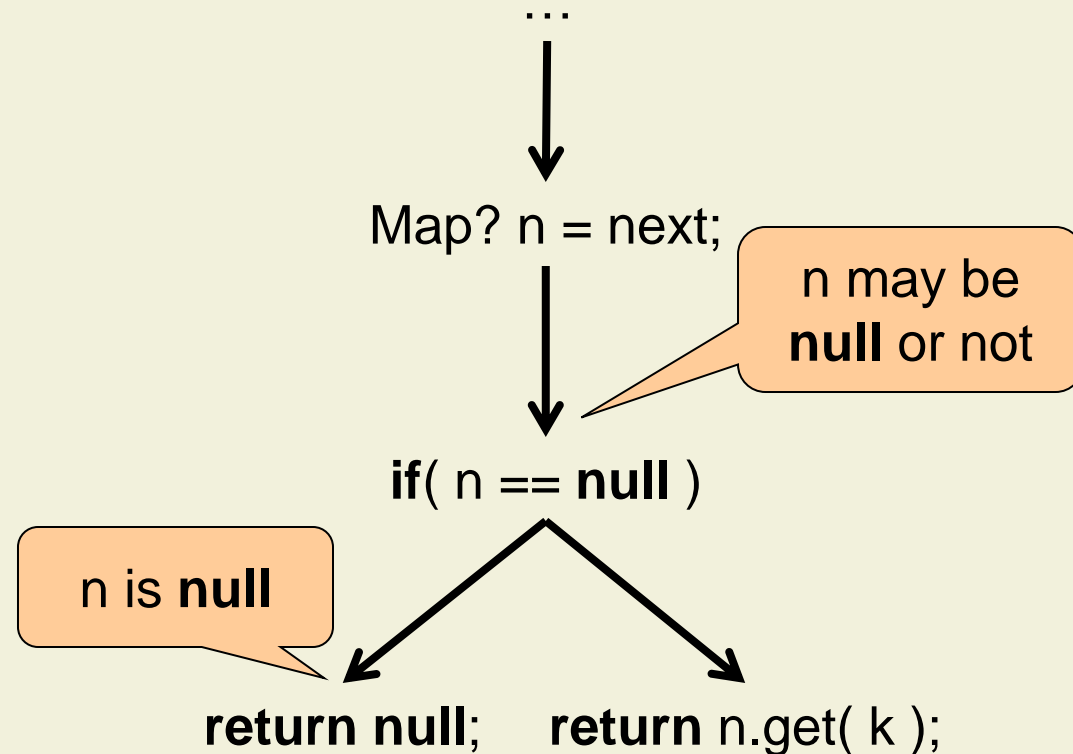
Control Flow Graph



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 );  
  }  
}
```

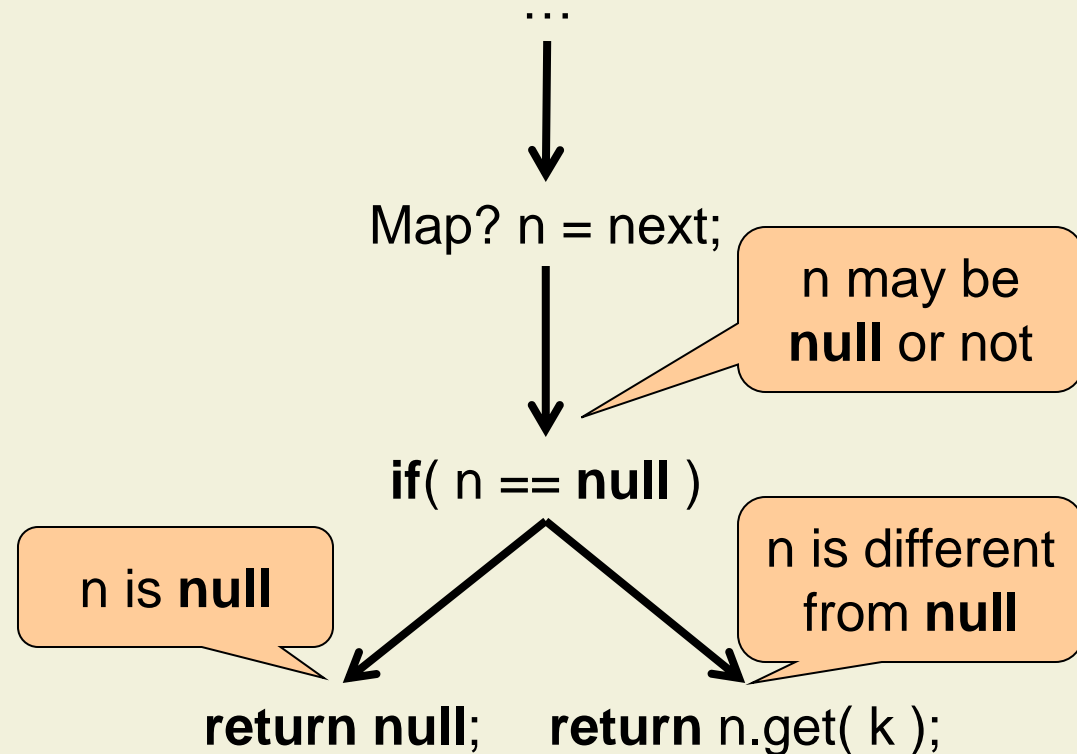
Control Flow Graph



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

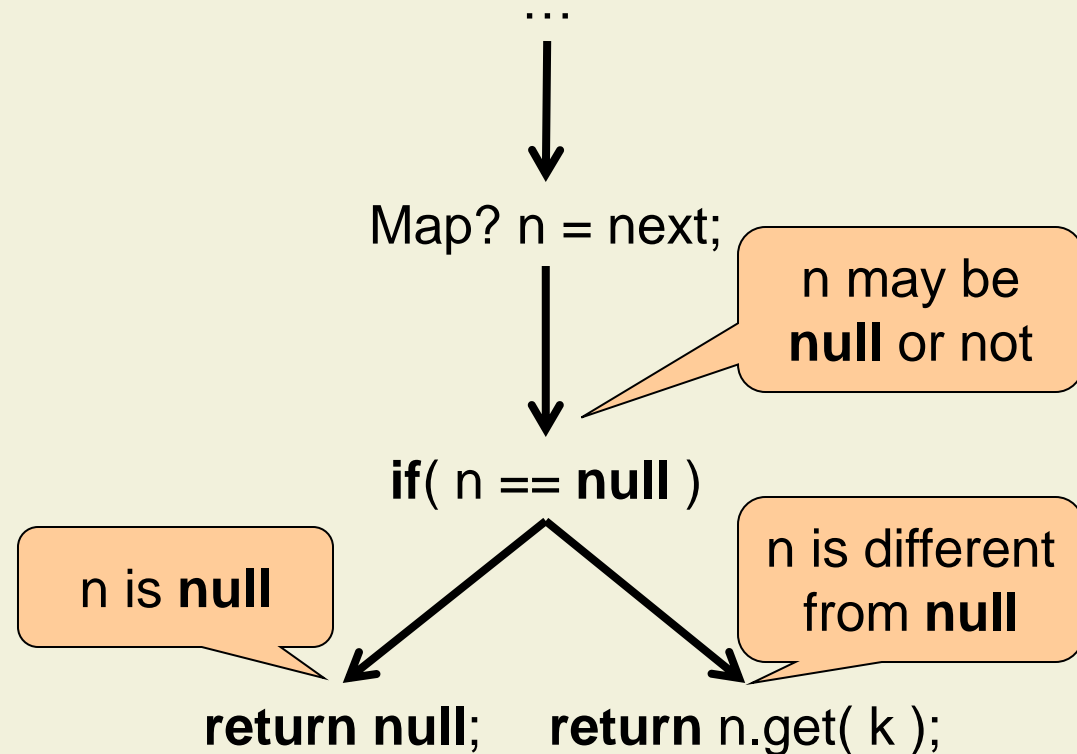


Comparing against null (cont'd)

```
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;  
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```

Limitations of Data Flow Analysis

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class Map {  
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    ...  
    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;  
}
```

- 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

7. Initialization

7.1 Simple Non-Null Types

7.2 Object Initialization

7.3 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;  
    Object! value;  
  
    Map( Object! k, Object! v ) {  
        key = k;  
        value = v;  
    }  
}
```

All fields are
initialized to **null**

Constructing New Objects

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class Map {  
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All fields are
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Type invariant is
violated here!

Constructing New Objects

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class Map {  
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}
```

All fields are
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Type invariant is
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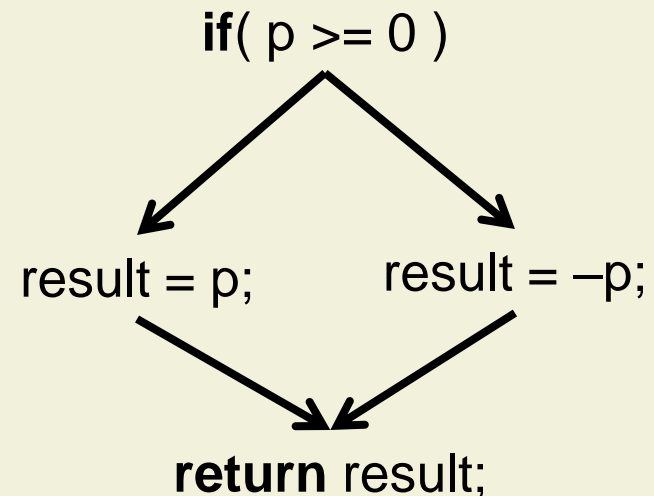
■ Idea:

- 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

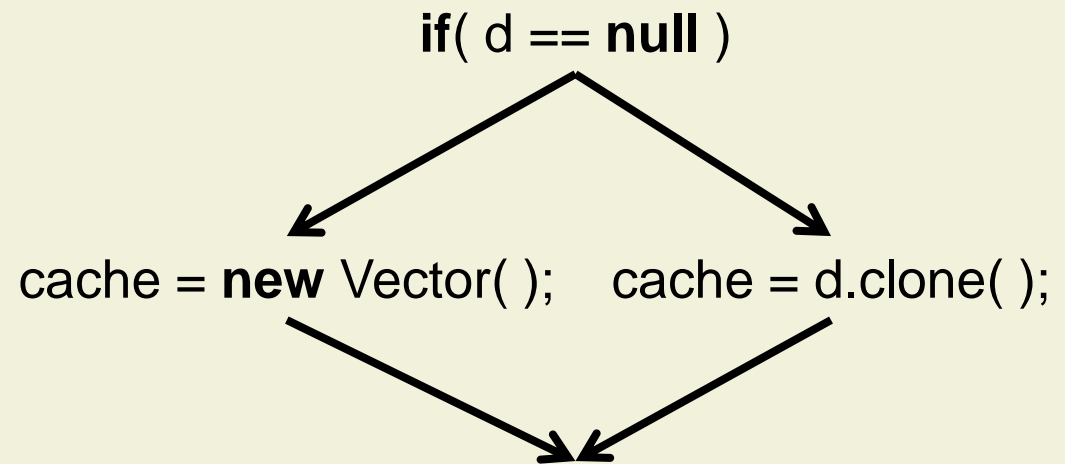
```
int abs( int p ) {  
    int result;  
    if( p >= 0 ) result = p;  
    else result = -p;  
    return result;  
}
```



Definite Assignment of Fields

- Idea: apply definite assignment rule for fields in constructor

```
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

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

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

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


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    Vector! cache;  
  
    Demo( ) {  
        int size = optimalSize( );  
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    }  
  
    int optimalSize( ) {  
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class Sub extends Demo {  
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```

Implicit
super-call

```
Vector! v = new Vector( );  
Sub! s = new Sub( v );
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    Demo( ) {  
        int size = optimalSize( );  
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        return 16;  
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```

Dynamically
bound

```
class Sub extends Demo {  
    Vector! data;  
  
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class Demo {  
    Vector! cache;  
  
    Demo( ) {  
        int size = optimalSize( );  
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    int optimalSize( ) {  
        return 16;  
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class Sub extends Demo {  
    Vector! data;  
  
    Sub( Vector! d ) {  
        data = d.clone( );  
    }  
  
    int optimalSize( ) {  
        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( ) ... }  
}
```

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

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class Demo implements Observer {  
    static Subject! subject;  
  
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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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class Subject {  
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class Sub extends Demo  
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}
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class Sub extends Demo  
    Vector! data;  
  
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}
```

Implicit
super-call

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    void register( Observer! o ) {  
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    }  
}
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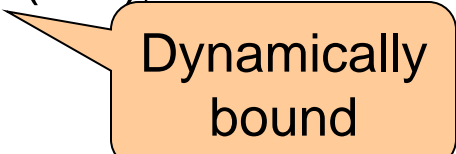
Dynamically
bound

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```


Problem 2: Call-backs

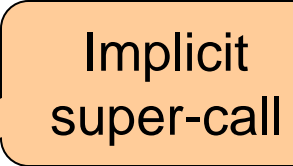
```
class Demo implements Observer {  
    static Subject! subject;  
  
    Demo( ) {  
        subject.register( this );  
    }  
  
    void update( ... ) { }  
}
```

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



Dynamically bound

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



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( ... );  
        }  
    }  
    ...  
}
```

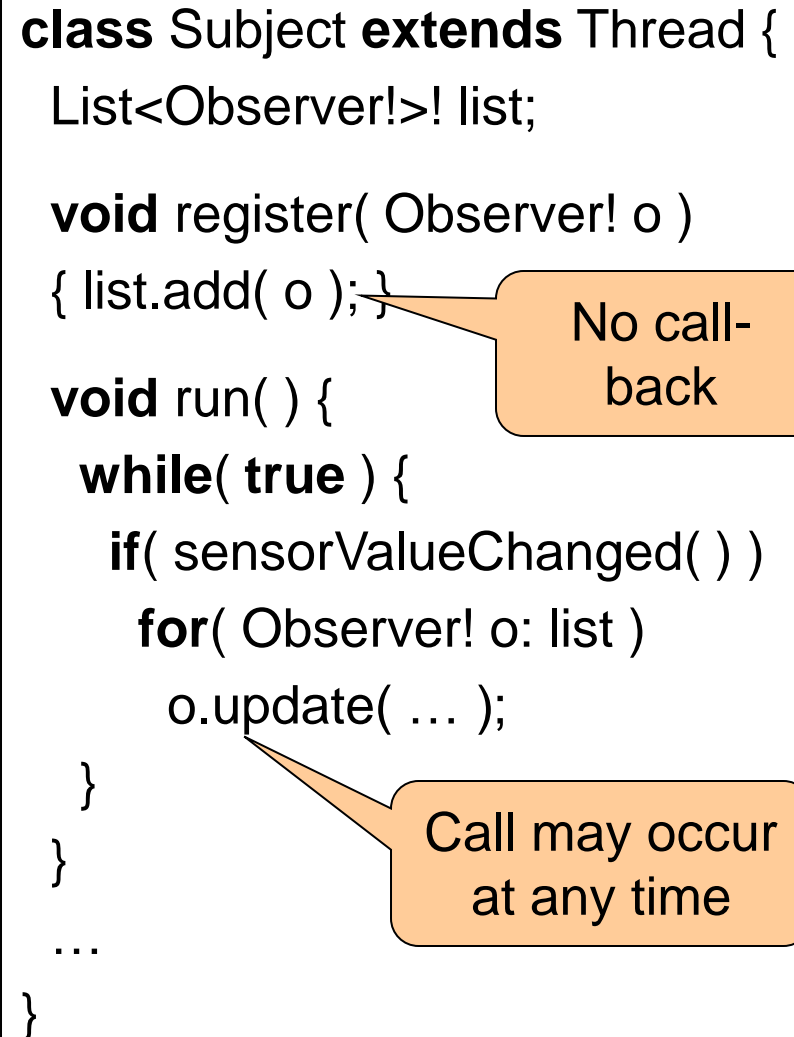
No call-back

Problem 3: Escaping via Method Calls

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

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

```
class Subject extends Thread {  
    List<Observer!>! list;  
  
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    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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class Subject extends Thread {  
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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 passed as receiver or argument to a method call
 - 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
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 - 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

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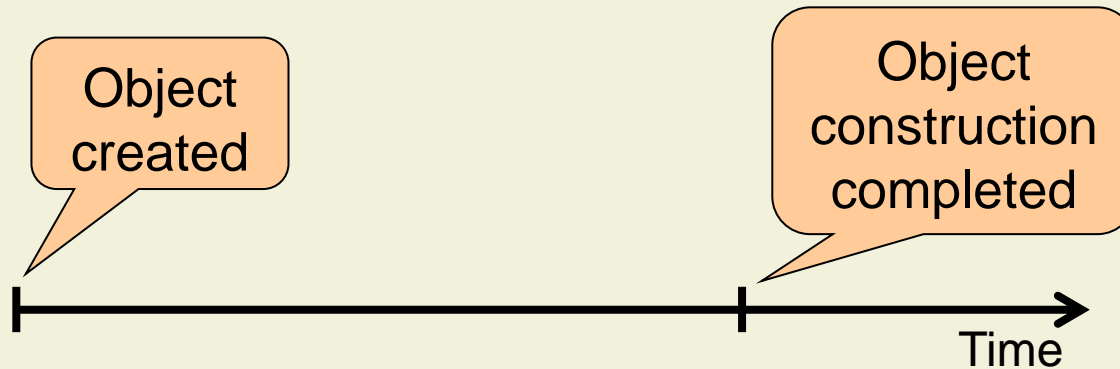
```
class Node {  
    Node! next; // a  
    String! label;  
  
    Node( String! l ) {  
        this.next = this;  
        this.setLabel( l );  
    }  
  
    void setLabel( String! l ) {  
        this.label = l;  
    }  
}
```

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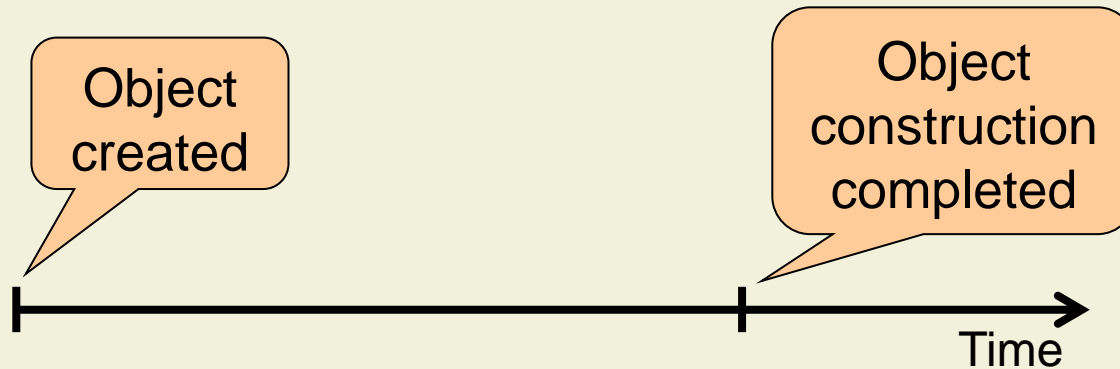
Method call is safe:
no reading of fields
of new object

Initialization Phases

Initialization Phases

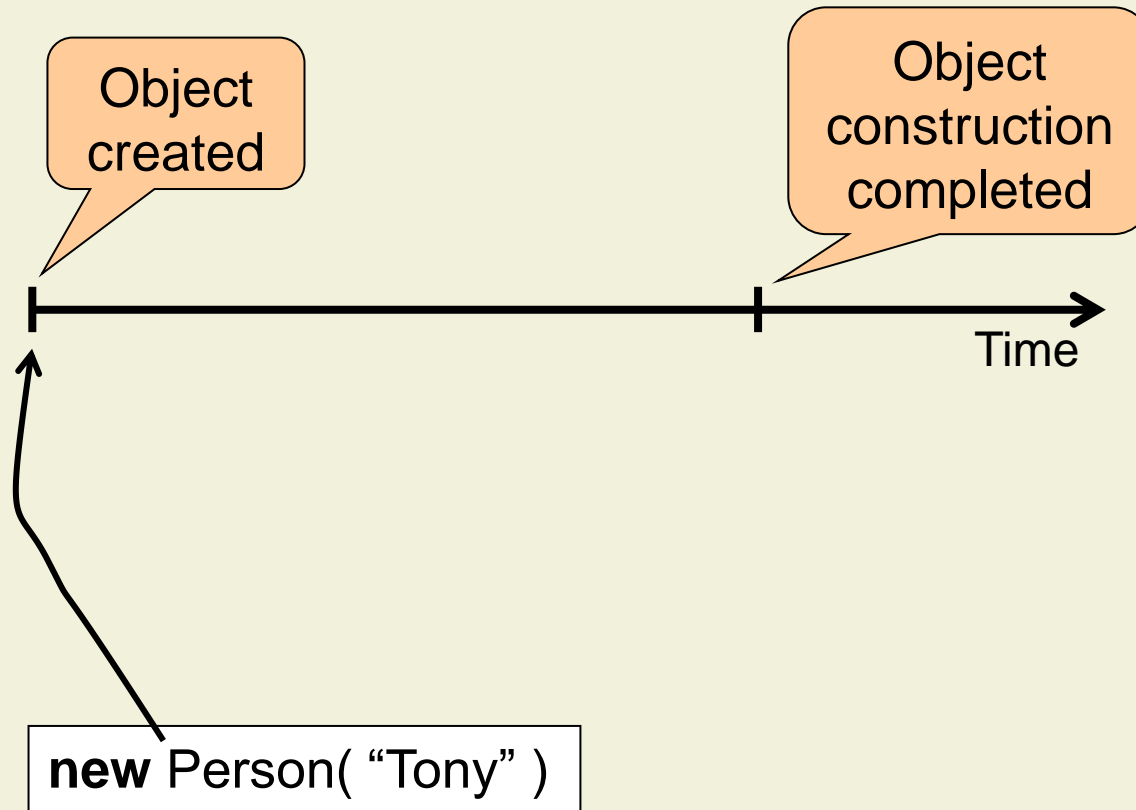


Initialization Phases

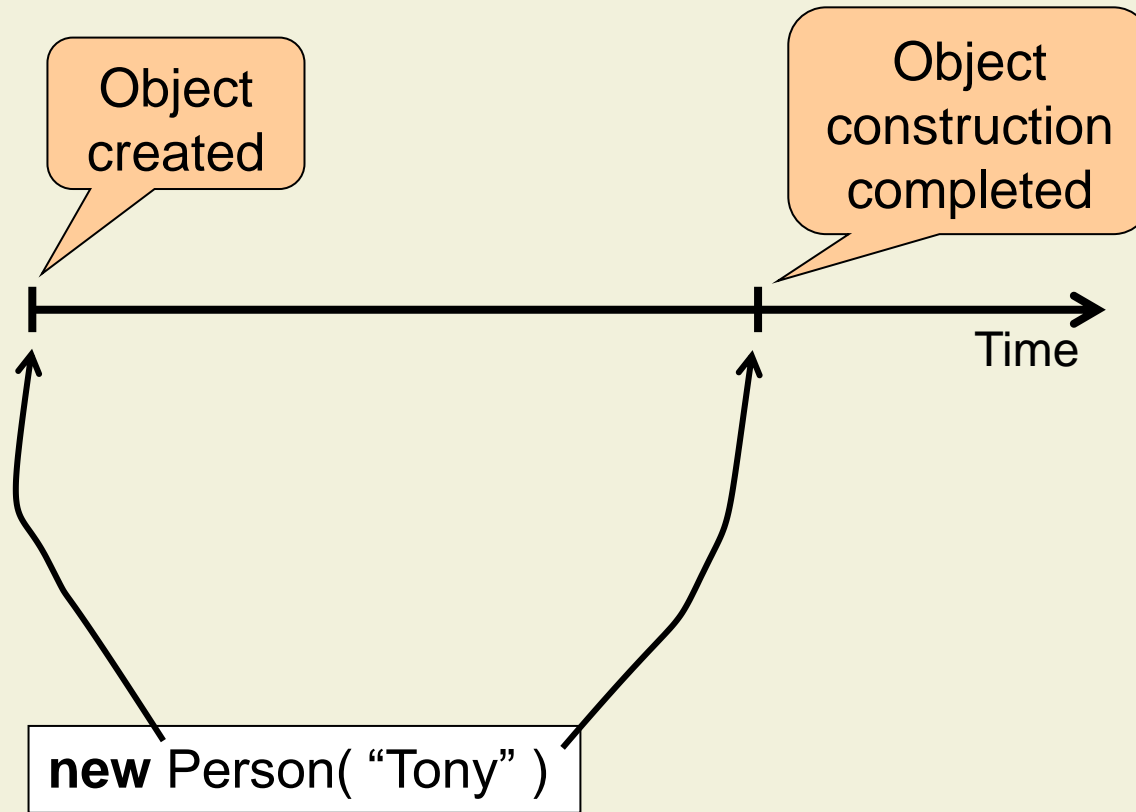


```
new Person( "Tony" )
```

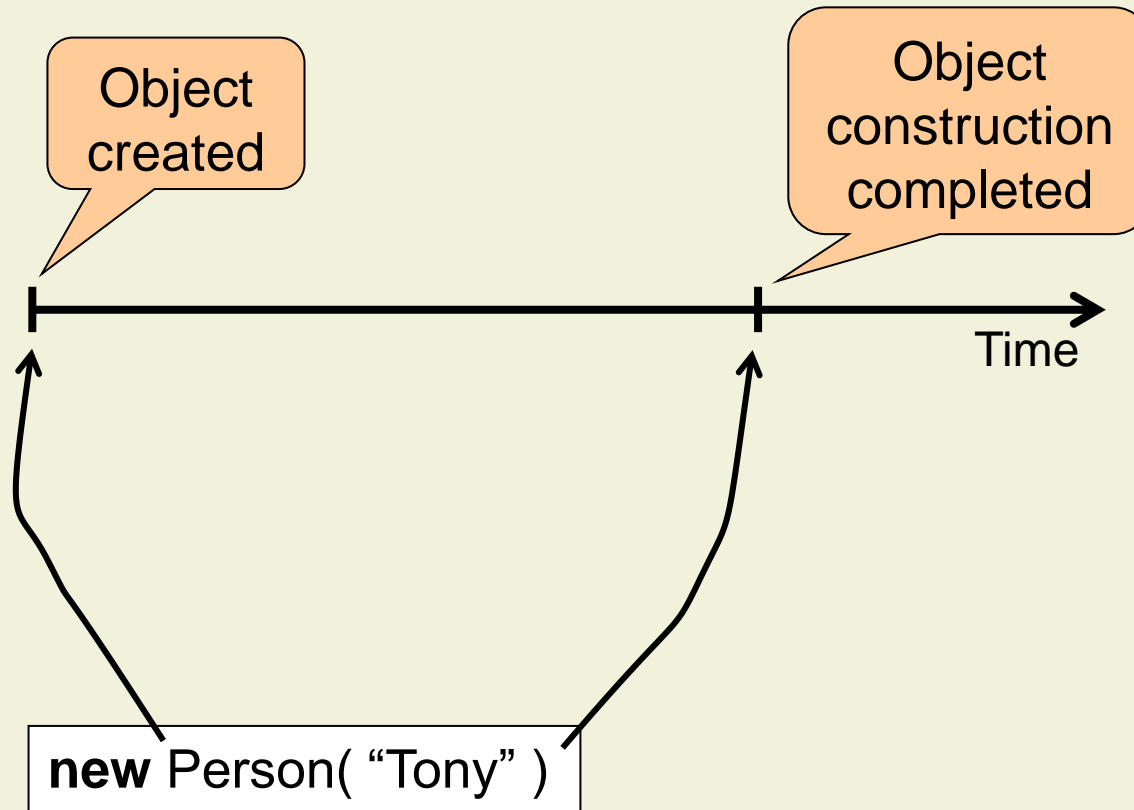
Initialization Phases



Initialization Phases

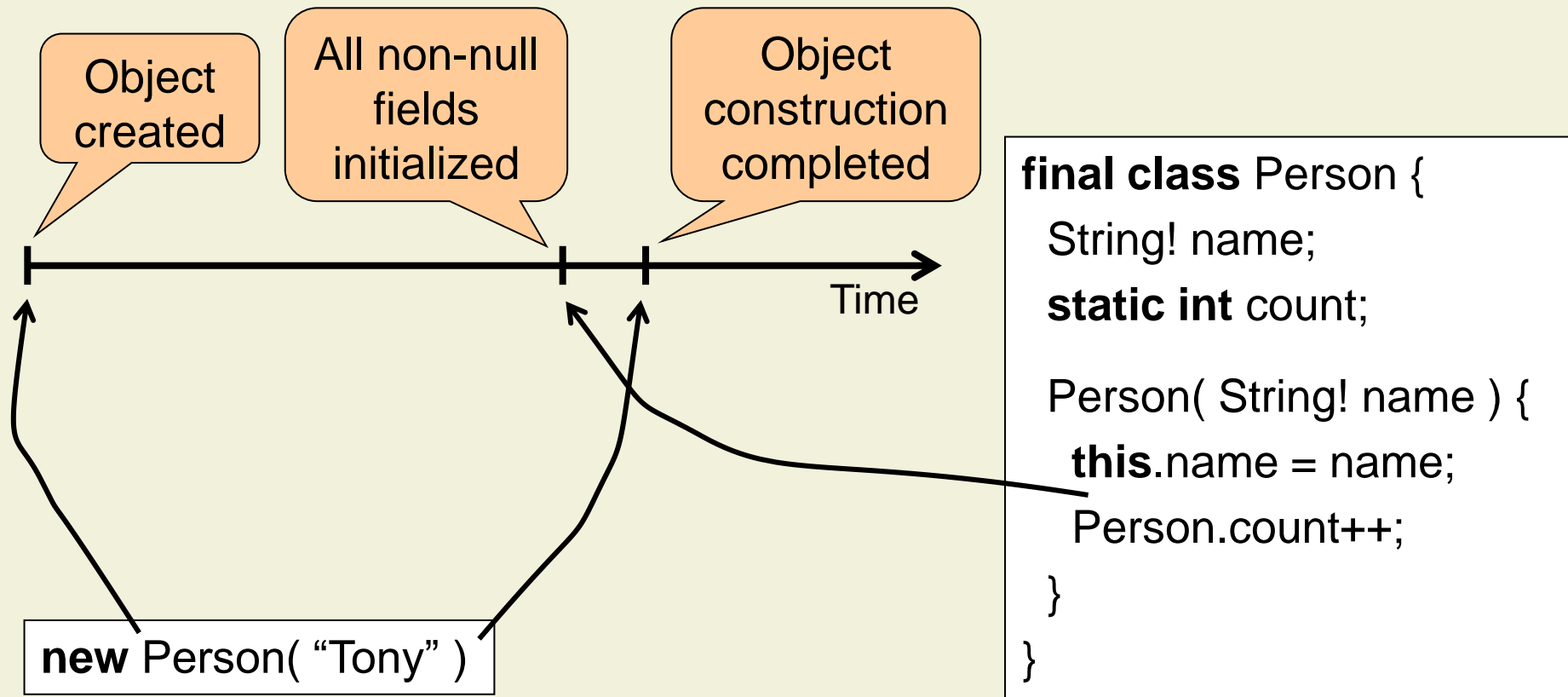


Initialization Phases

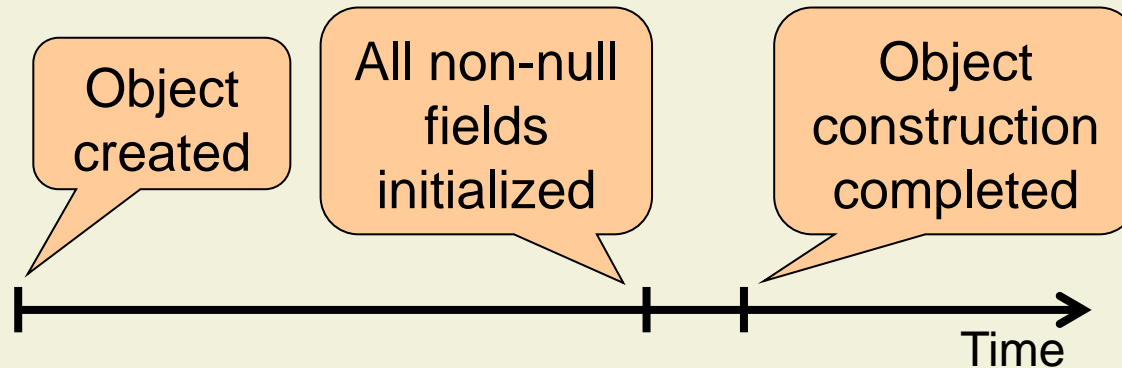


```
final class Person {  
    String! name;  
    static int count;  
  
    Person( String! name ) {  
        this.name = name;  
        Person.count++;  
    }  
}
```

Initialization Phases

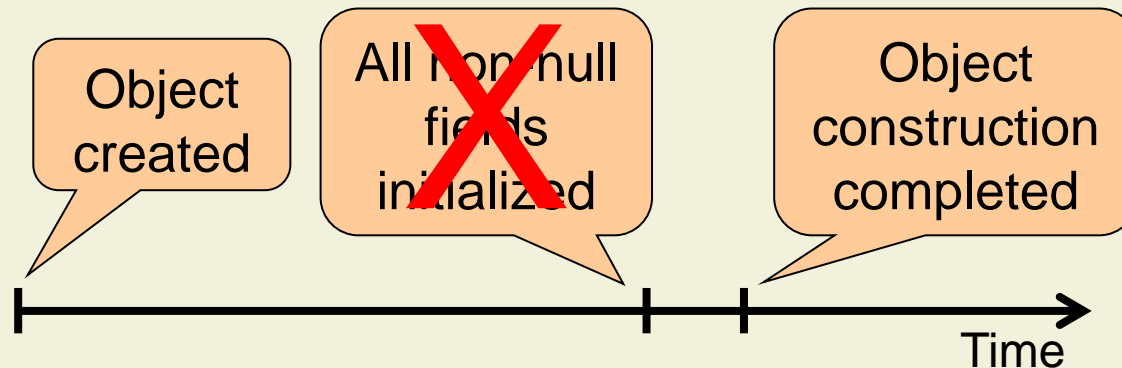


Tracking Object Construction



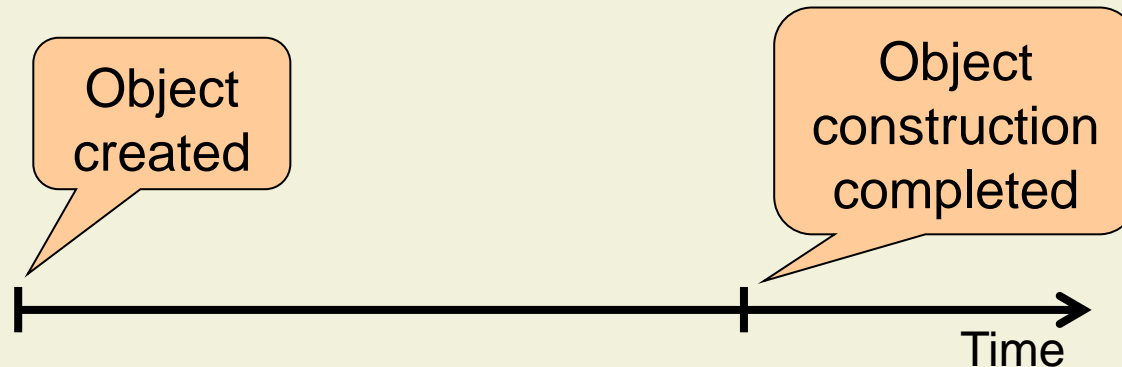
- Idea: design a type system that tracks **which objects are under construction**
 - For simplicity, we track whether the construction has completed (non-null fields may be initialized earlier)
- (Simplified) type invariant:
If the static type of an expression e is a non-null type then e 's value at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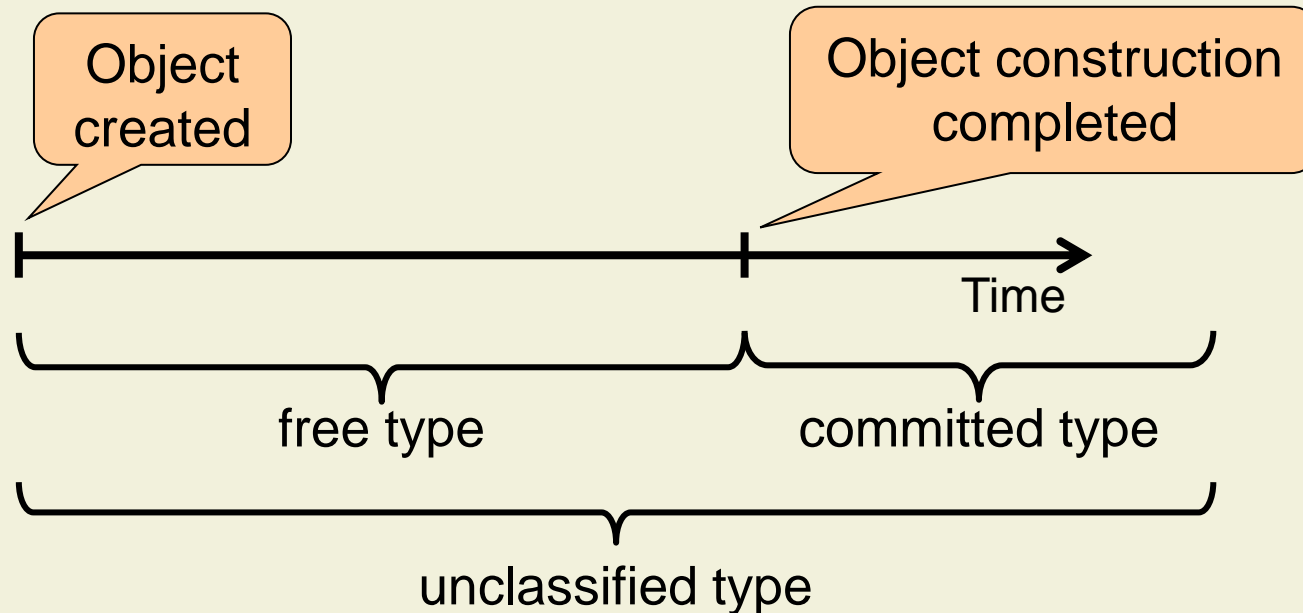
Tracking Object Construction



- 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

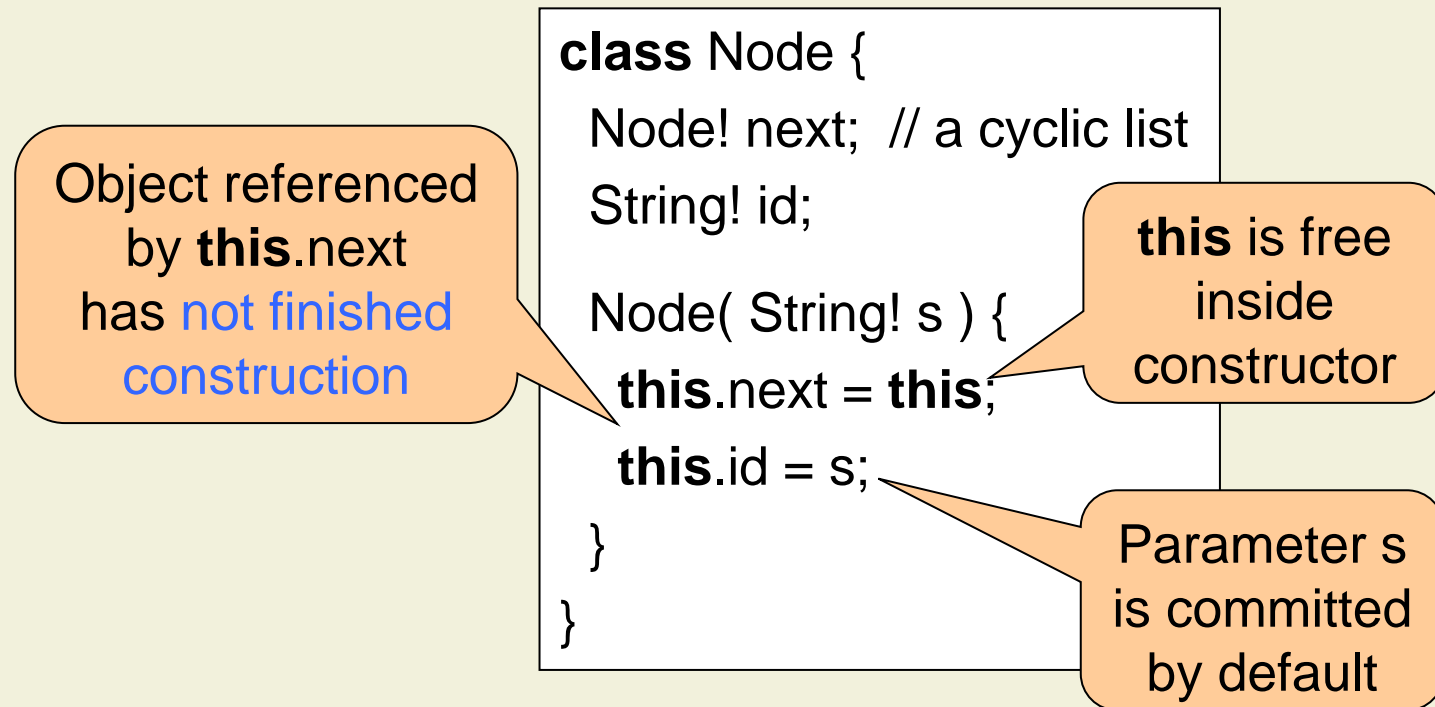
Requirement 3: Cyclic Structures

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

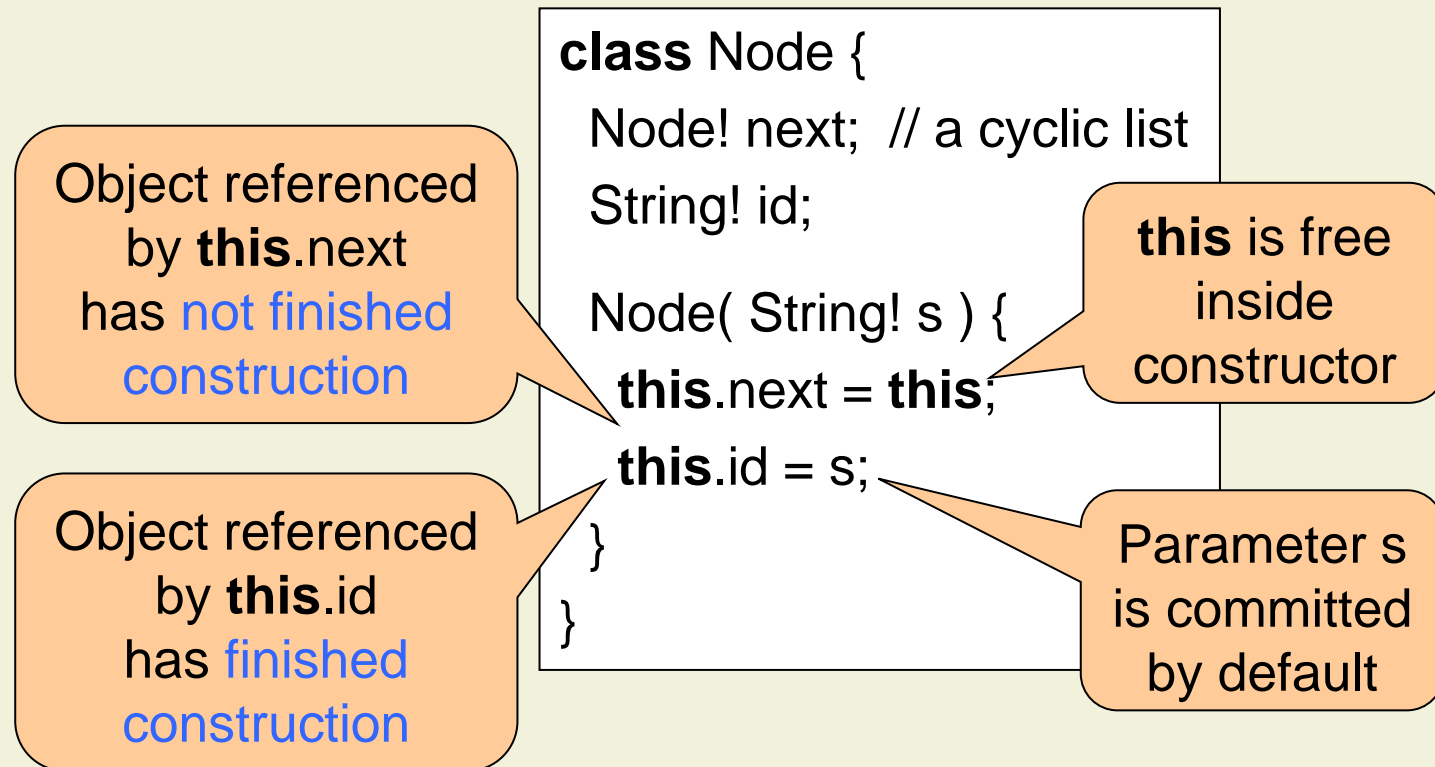
```
class Node {  
  Node! next; // a cyclic list  
  String! id;  
  
  Node( String! s ) {  
    this.next = this;  
    this.id = s;  
  }  
}
```

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

name is of a committed type

```
class Node
Node! next
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.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

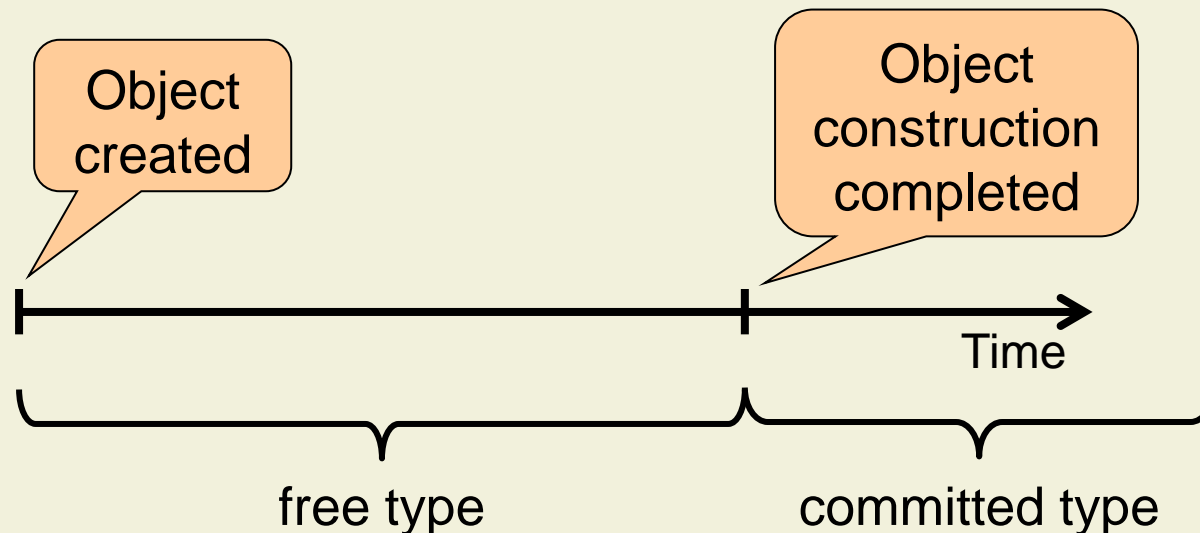
Type Rules: Methods and Calls

- 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

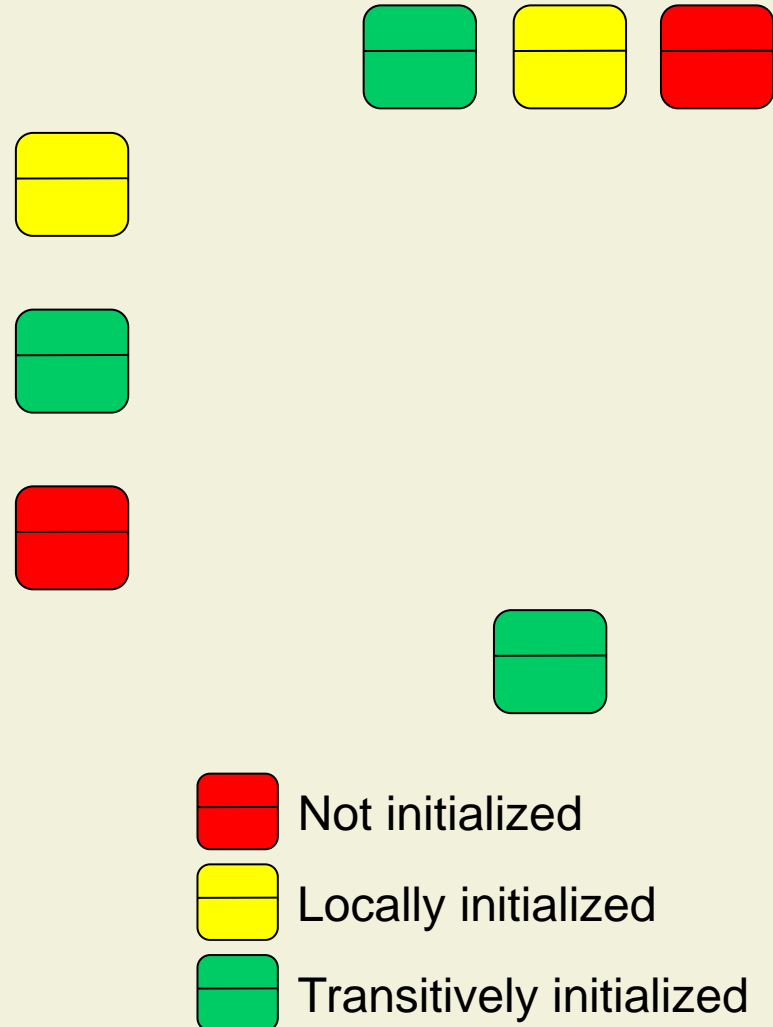
```
class C {  
    Demo! demo;  
    C( free Demo! d ) { demo = d; }  
    String! foo( ) { return demo.myC.toString( ); }  
}
```

NullPointerException

Object Construction

■ Assumptions

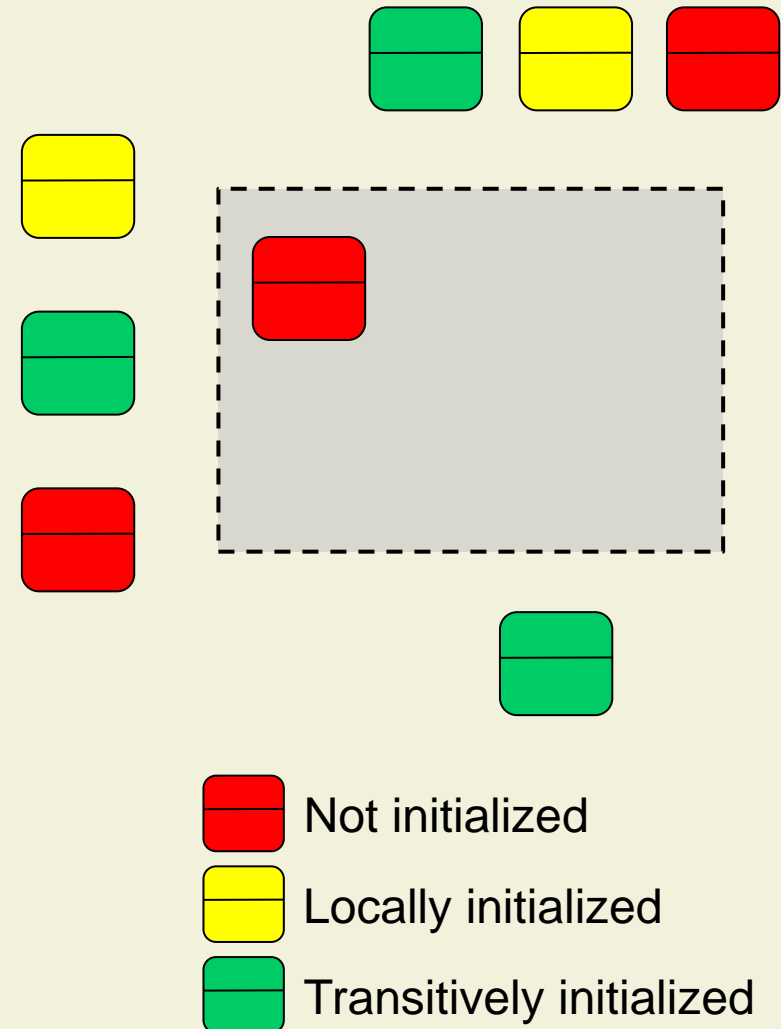
- new-expression takes **only committed arguments**
- Nested new-expressions take **arbitrary arguments**



Object Construction

■ Assumptions

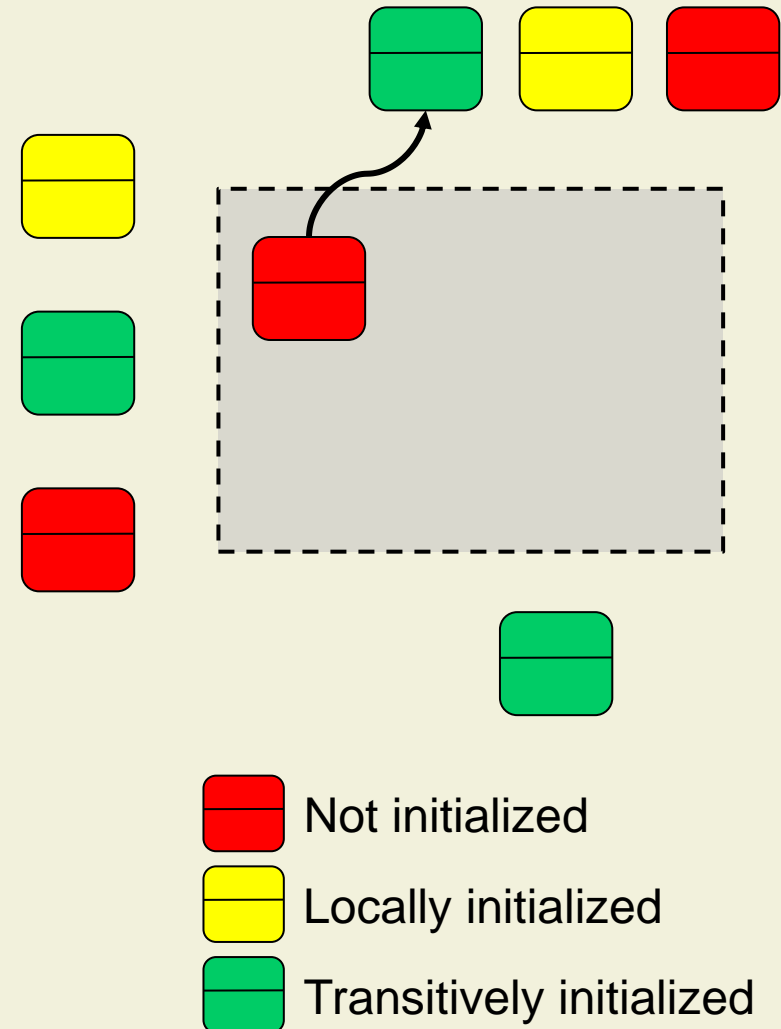
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Object Construction

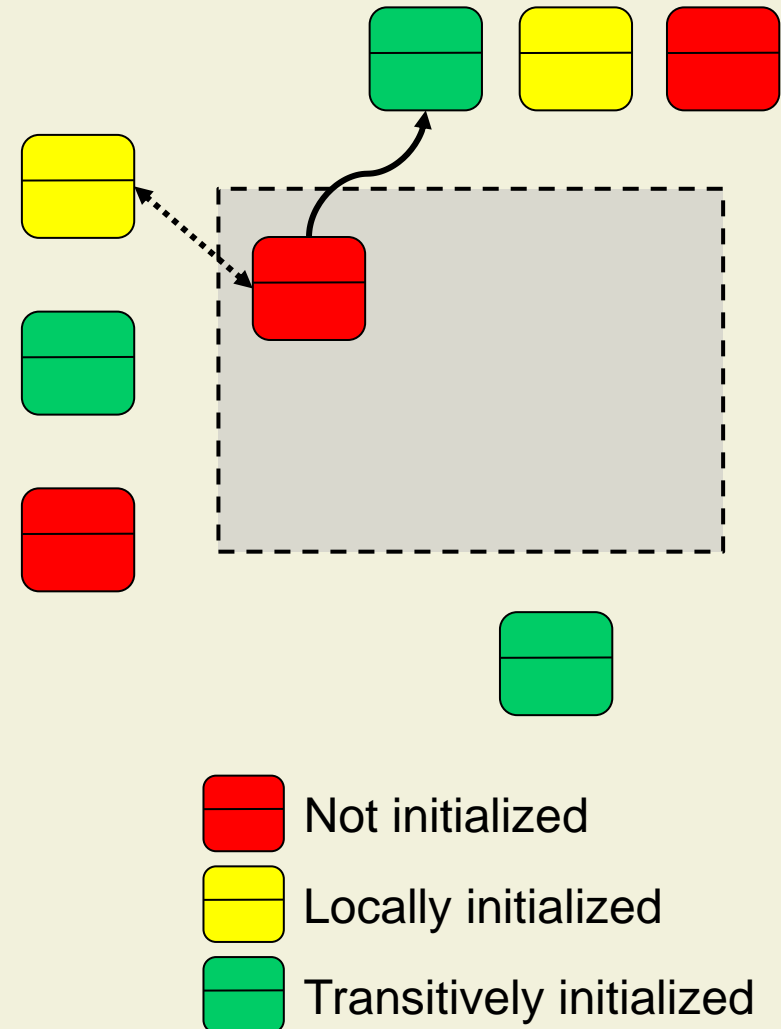
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Object Construction

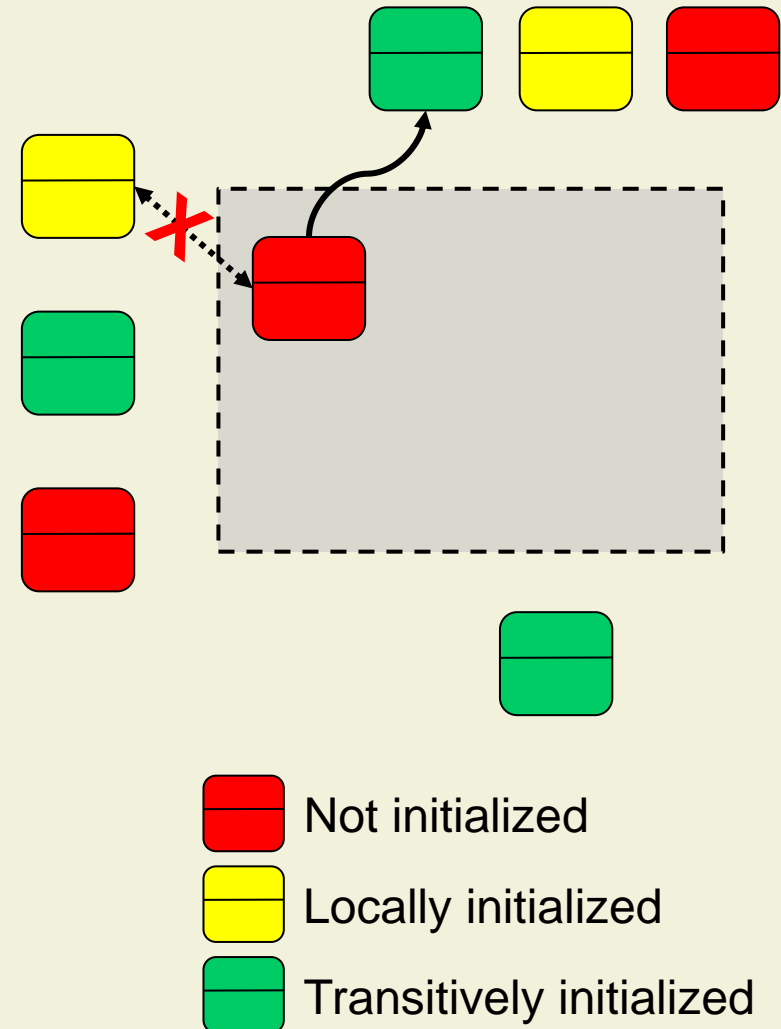
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Object Construction

■ Assumptions

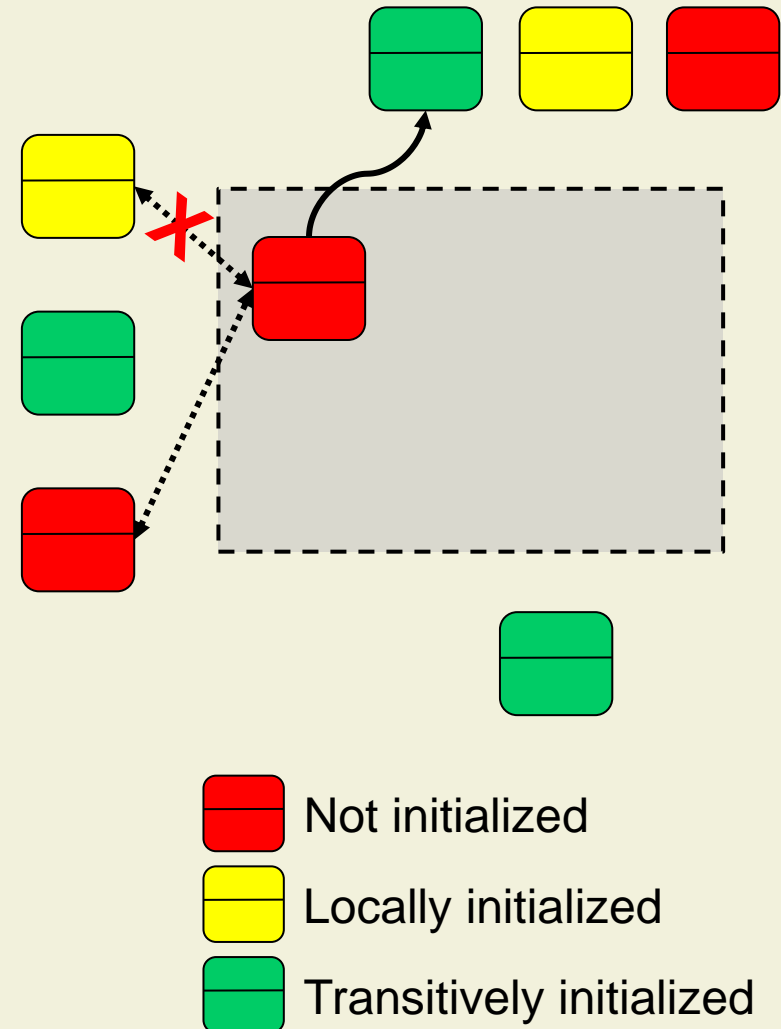
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Object Construction

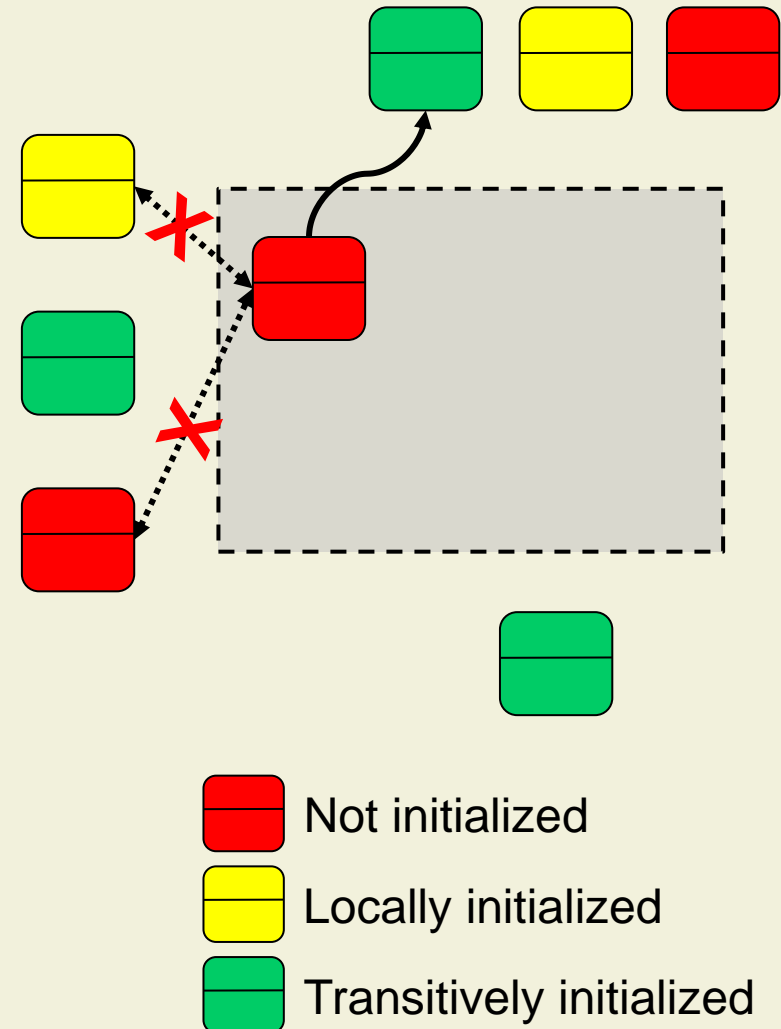
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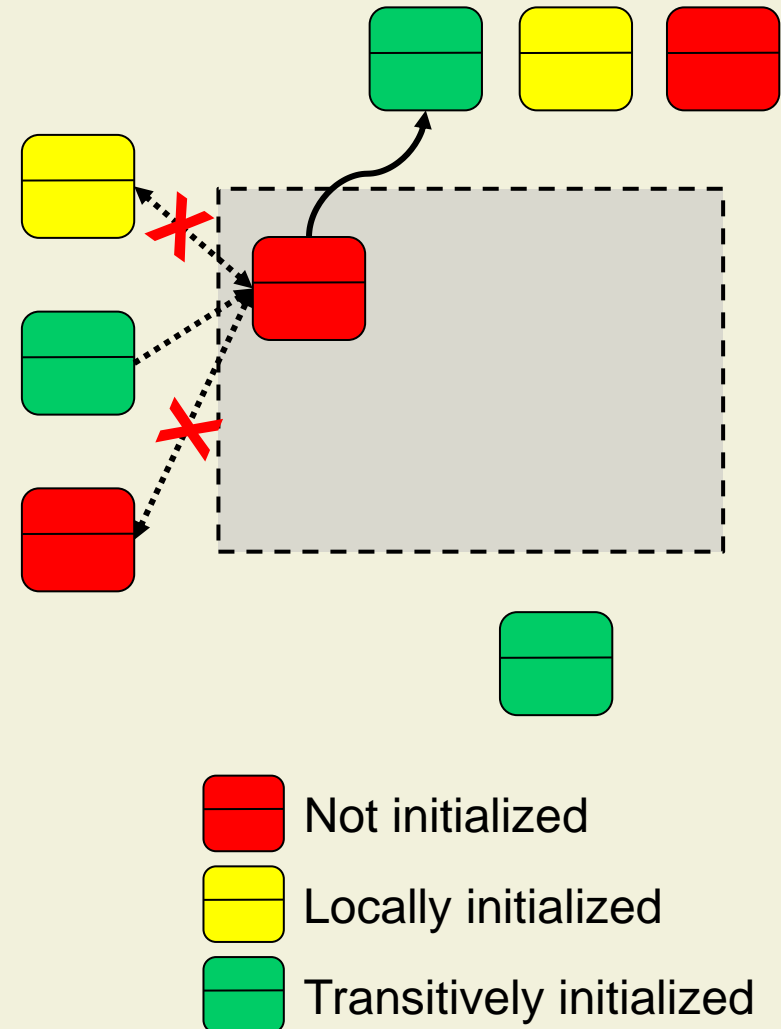
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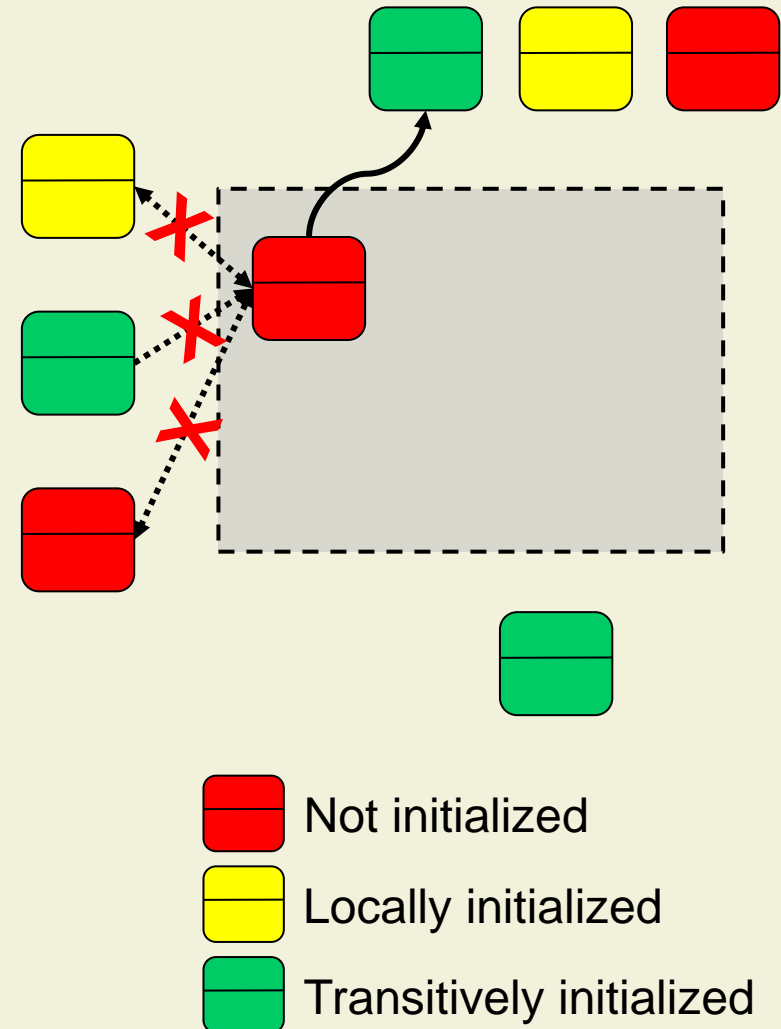
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Object Construction

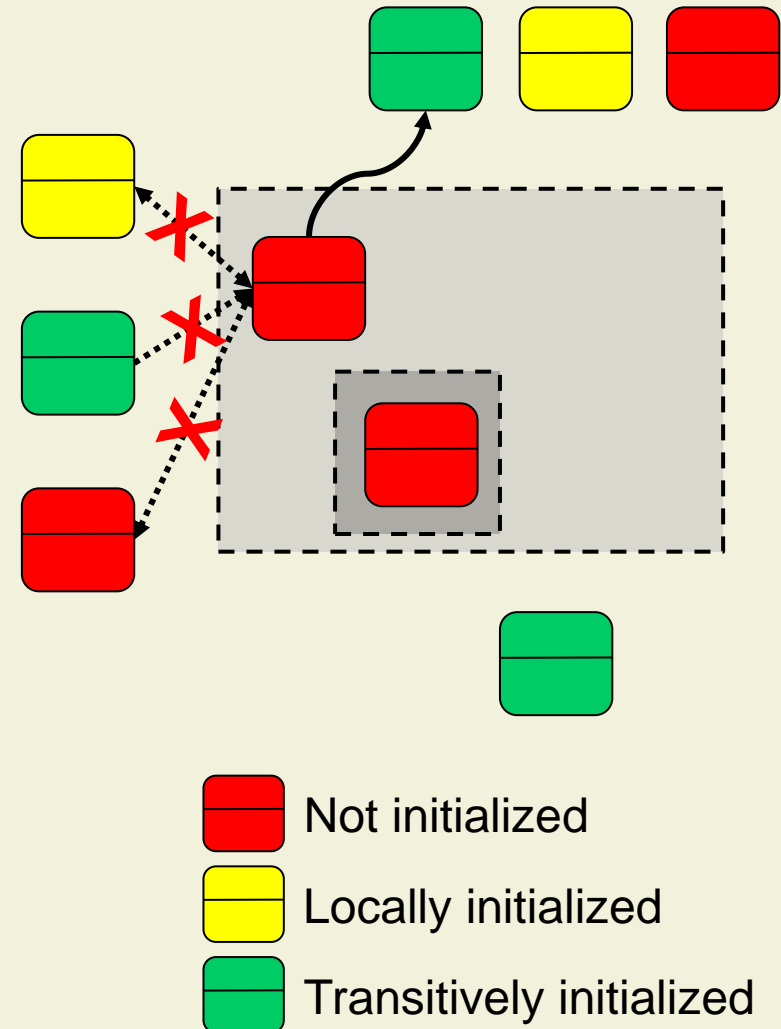
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Object Construction

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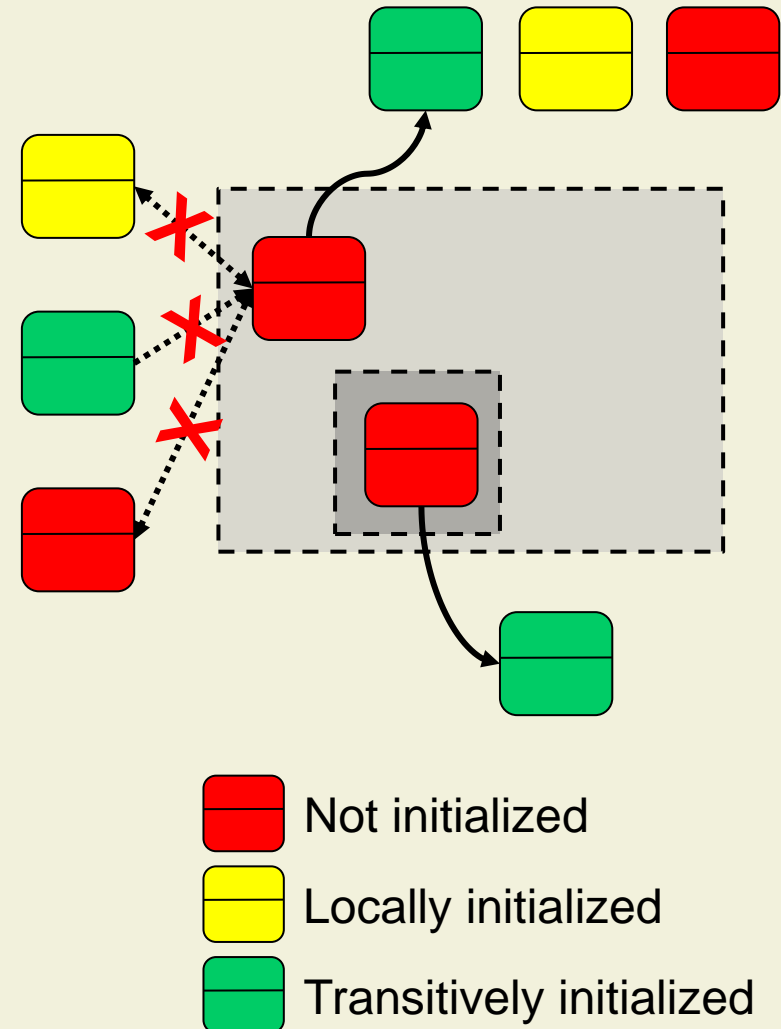
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Object Construction

■ Assumptions

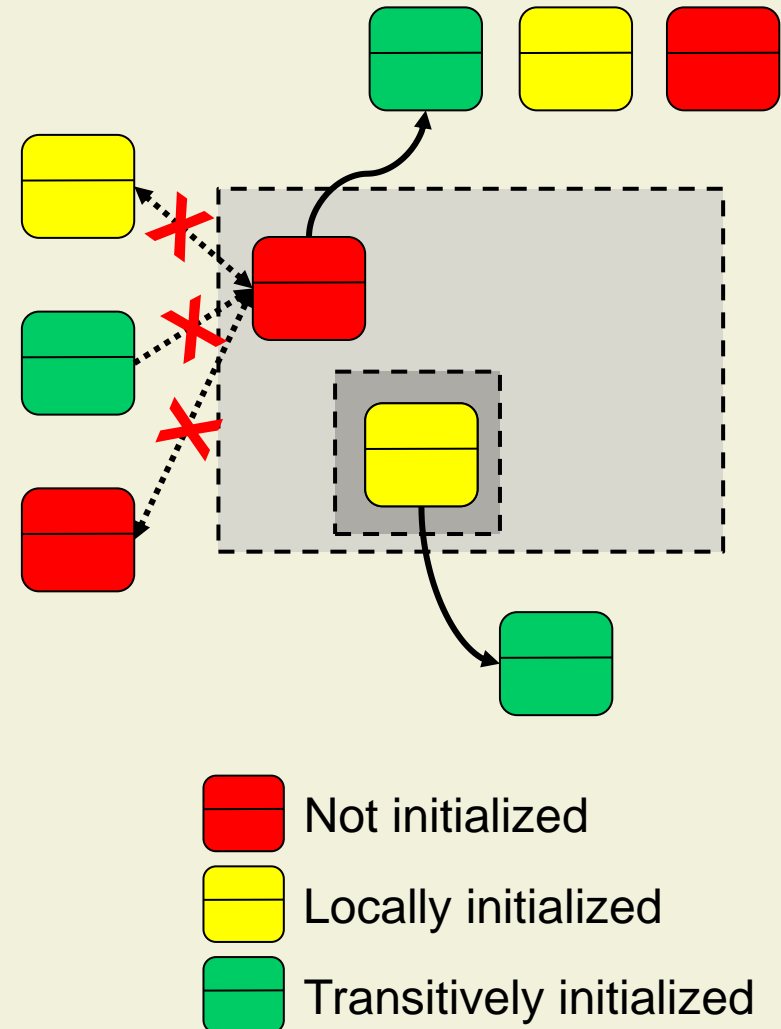
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Object Construction

■ Assumptions

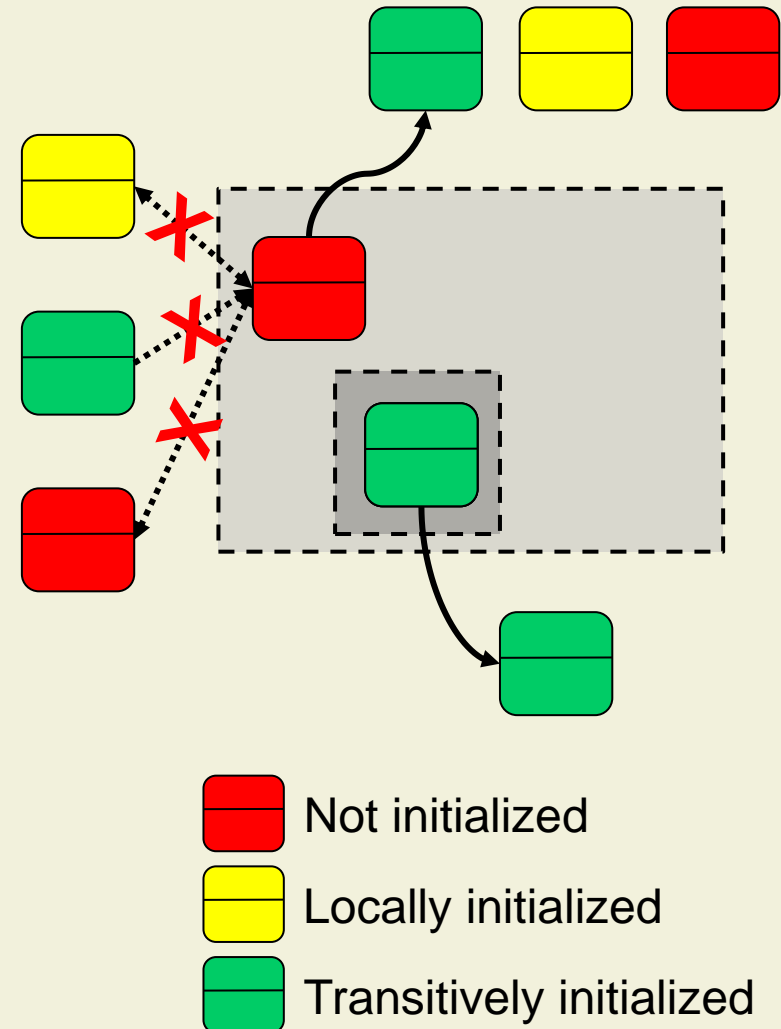
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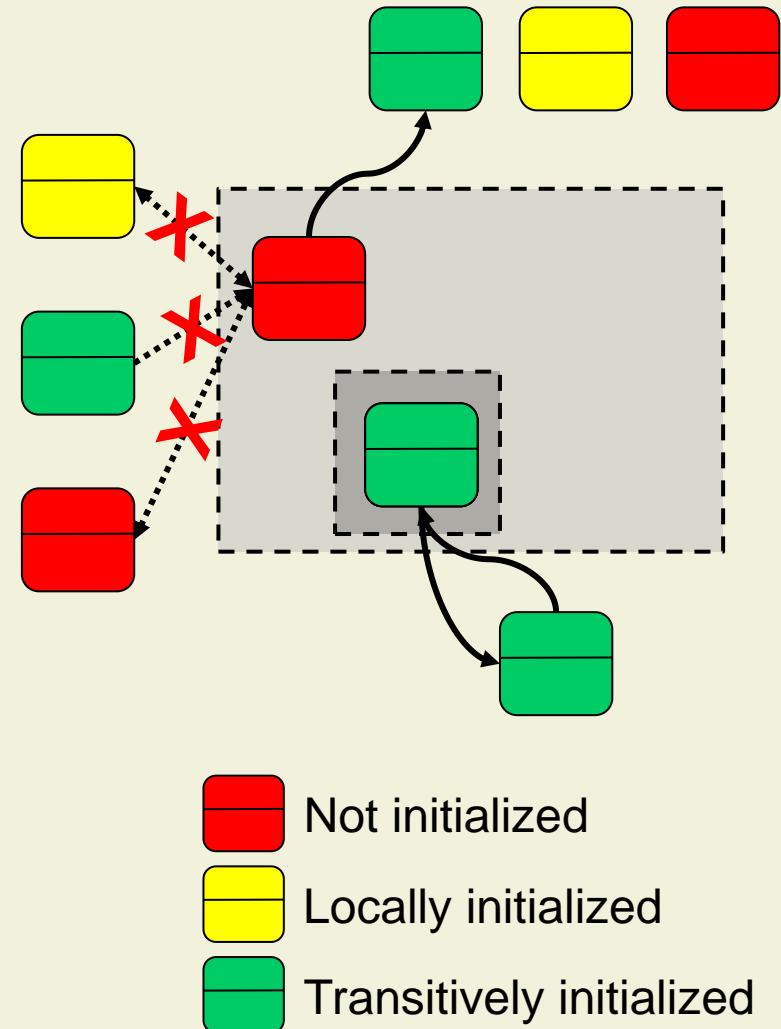
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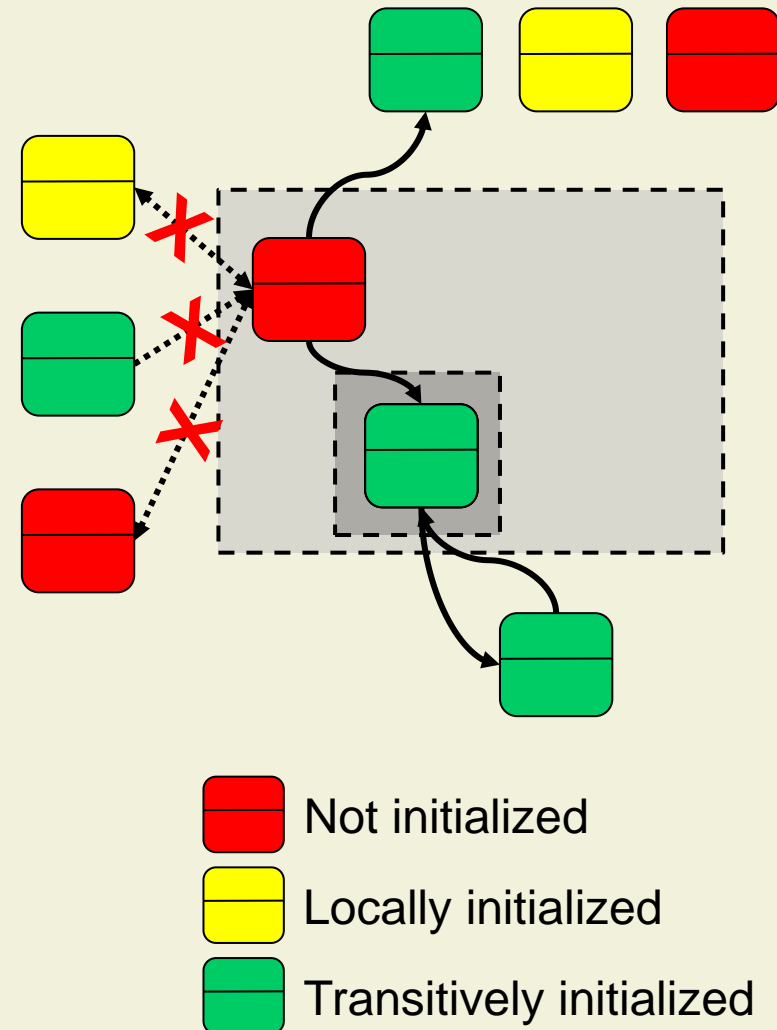
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Object Construction

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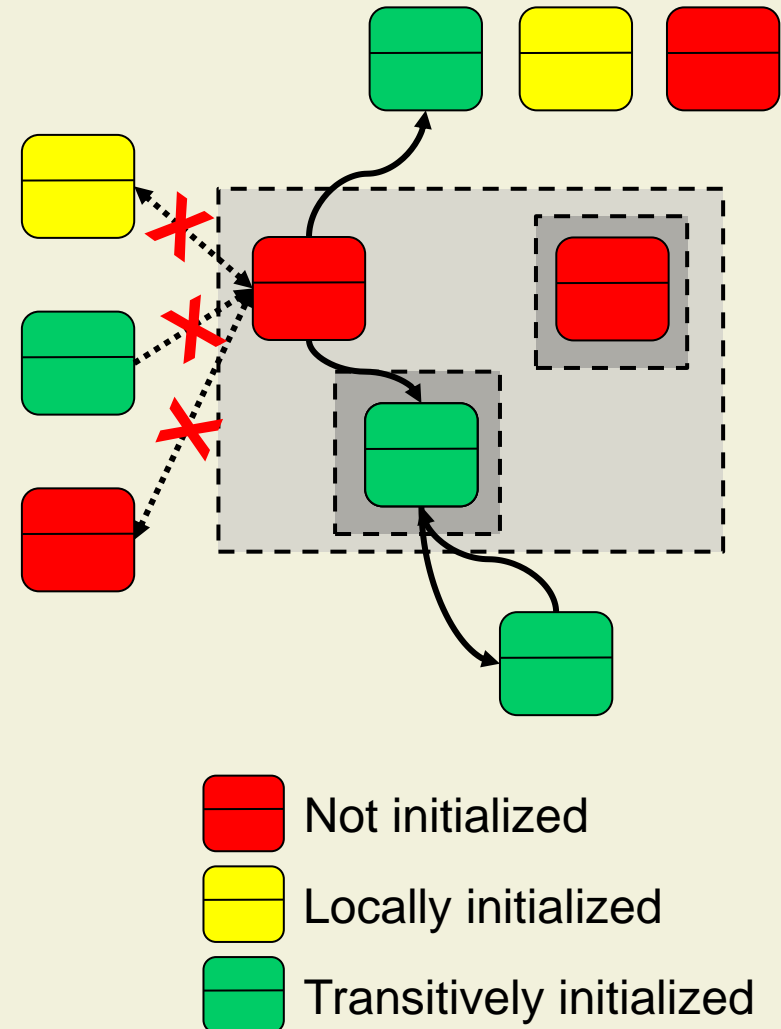
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Object Construction

Assumptions

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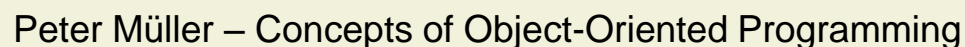


- Assumptions

-
- The diagram illustrates the concept of transitive initialization in a graph structure. It shows a central gray-shaded region containing several nodes (squares) and edges (arrows). The nodes are colored red, yellow, or green, representing different initialization states. Red nodes are 'Not initialized', yellow nodes are 'Locally initialized', and green nodes are 'Transitively initialized'. The legend at the bottom defines these colors: a red square for 'Not initialized', a yellow square for 'Locally initialized', and a green square for 'Transitively initialized'.
- Legend:
- Not initialized (Red square)
 - Locally initialized (Yellow square)
 - Transitively initialized (Green square)

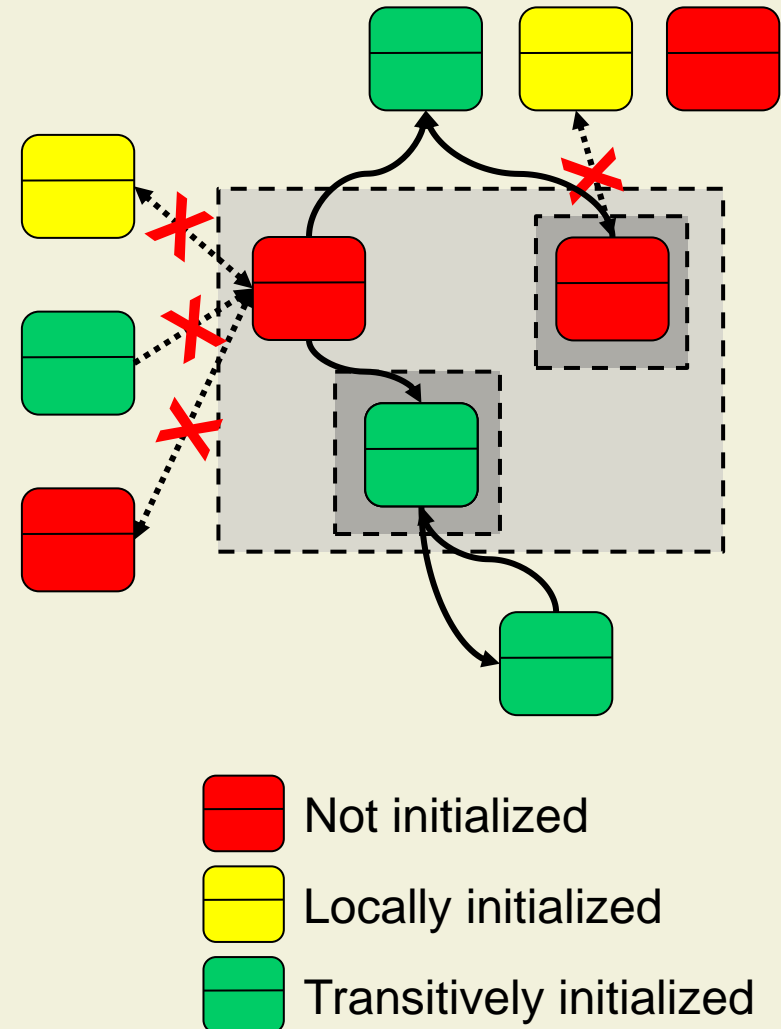
- Assumptions

-



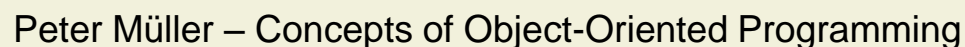
Object Construction

- Assumptions
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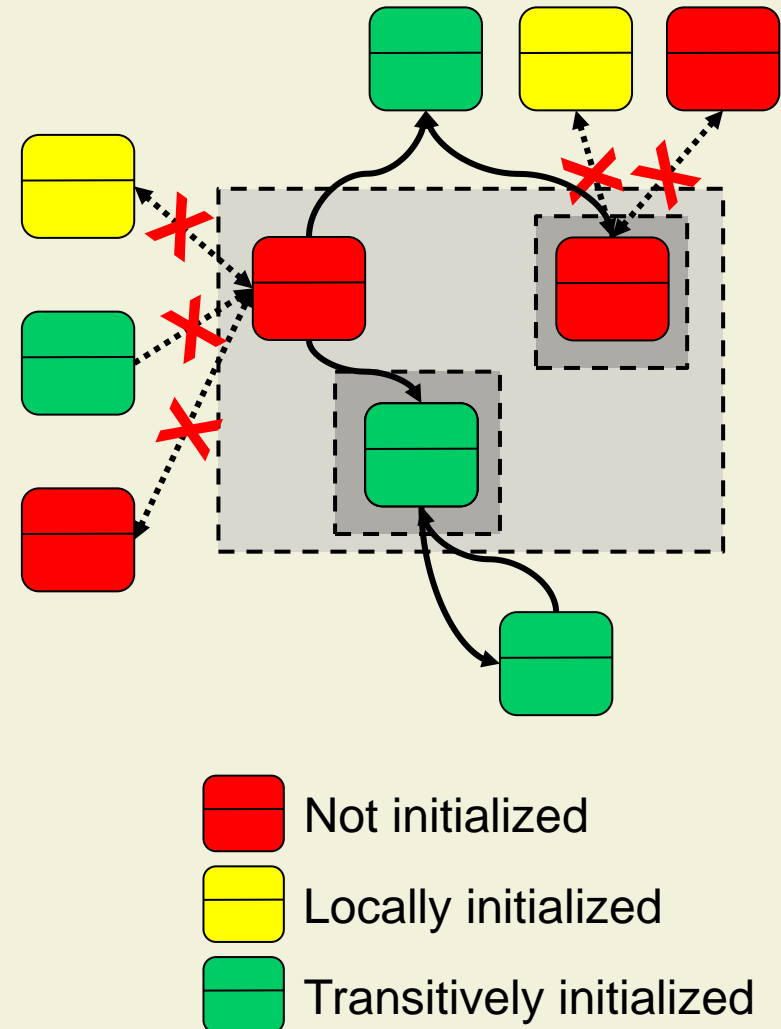
- Assumptions

-
- The diagram shows a directed graph with nodes represented as colored squares (yellow, green, red) divided horizontally. A large gray-shaded area contains a central red node, a green node below it, and a yellow node above it. A dashed box encloses the red node and the green node below it, indicating a strongly connected component. Red 'X' marks are placed on arrows pointing from the yellow node to the red node, from the green node to the red node, and from the red node to the yellow node, suggesting these connections are not part of the strongly connected component.



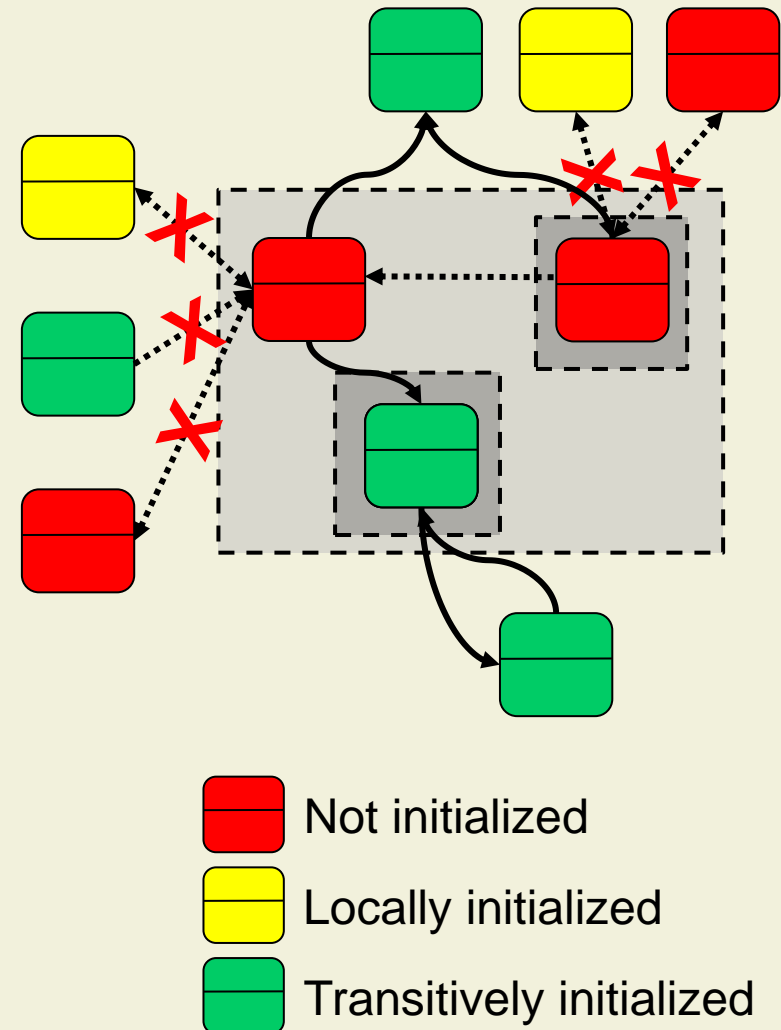
Object Construction

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Object Construction

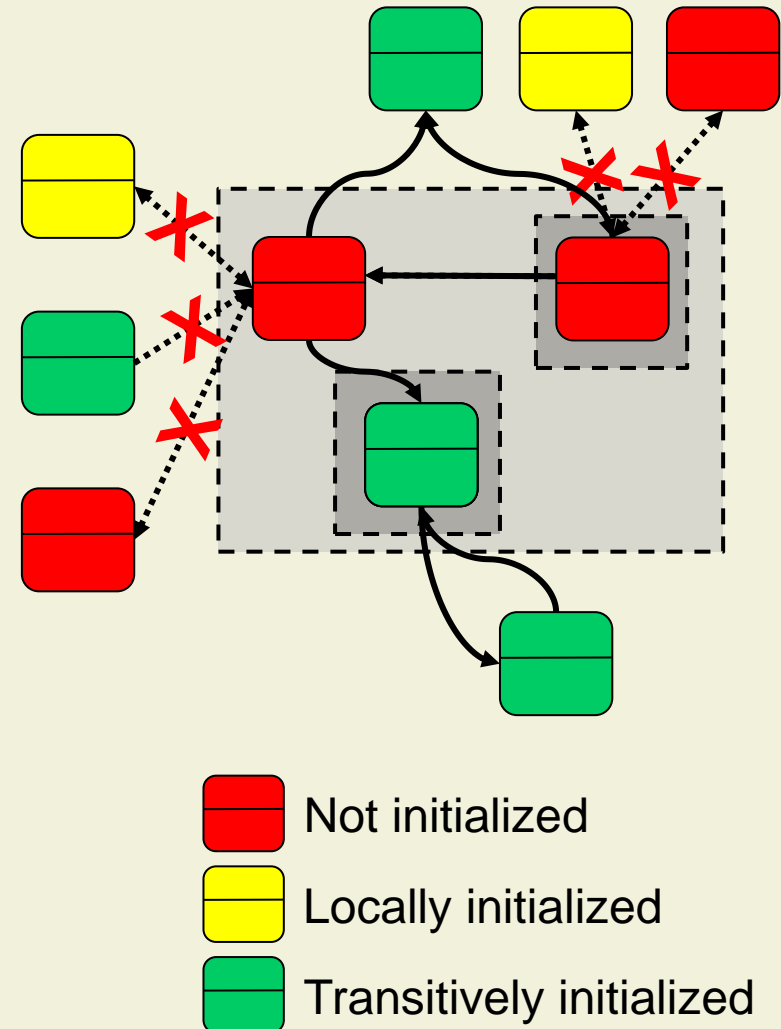
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Object Construction

■ Assumptions

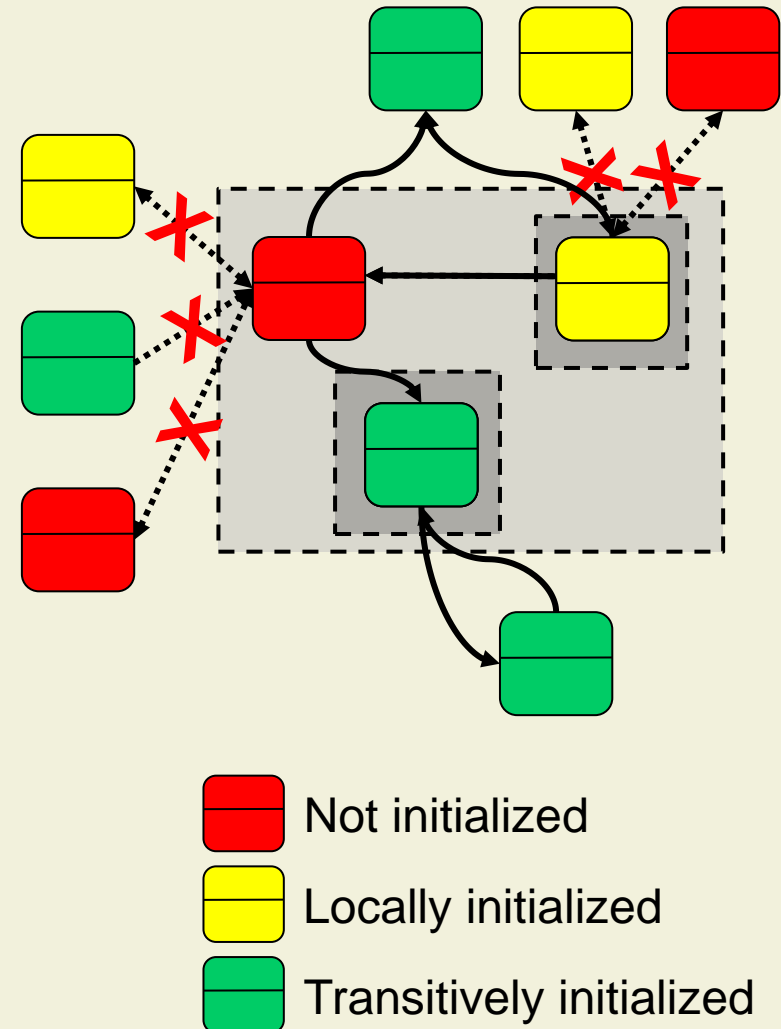
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Object Construction

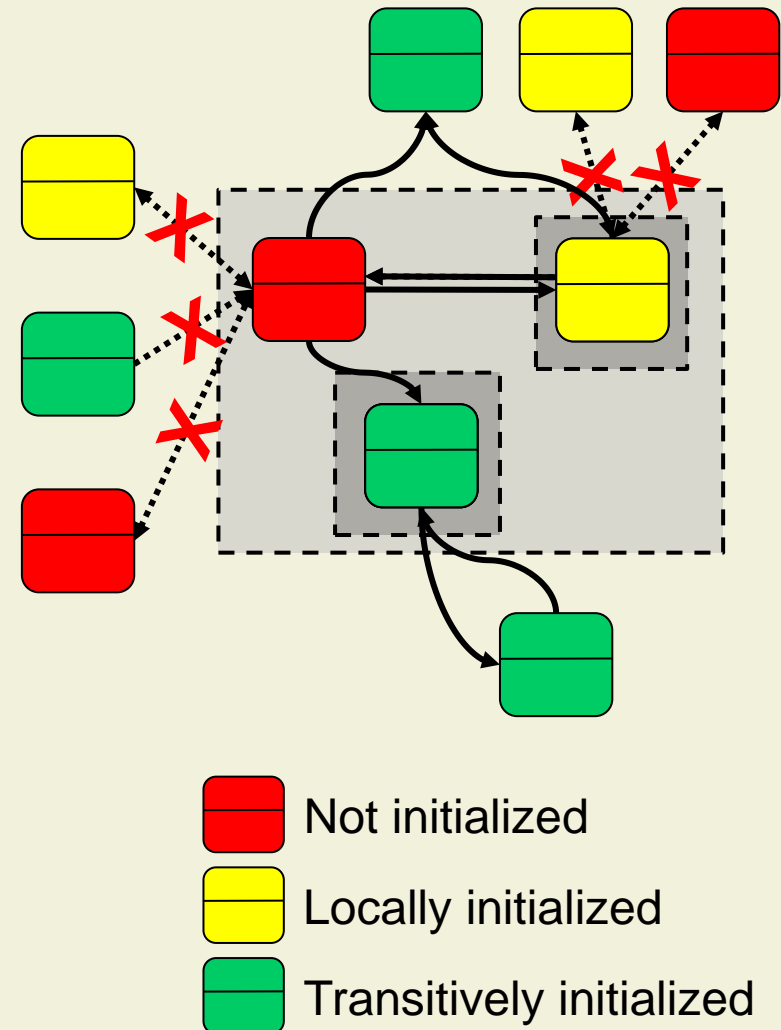
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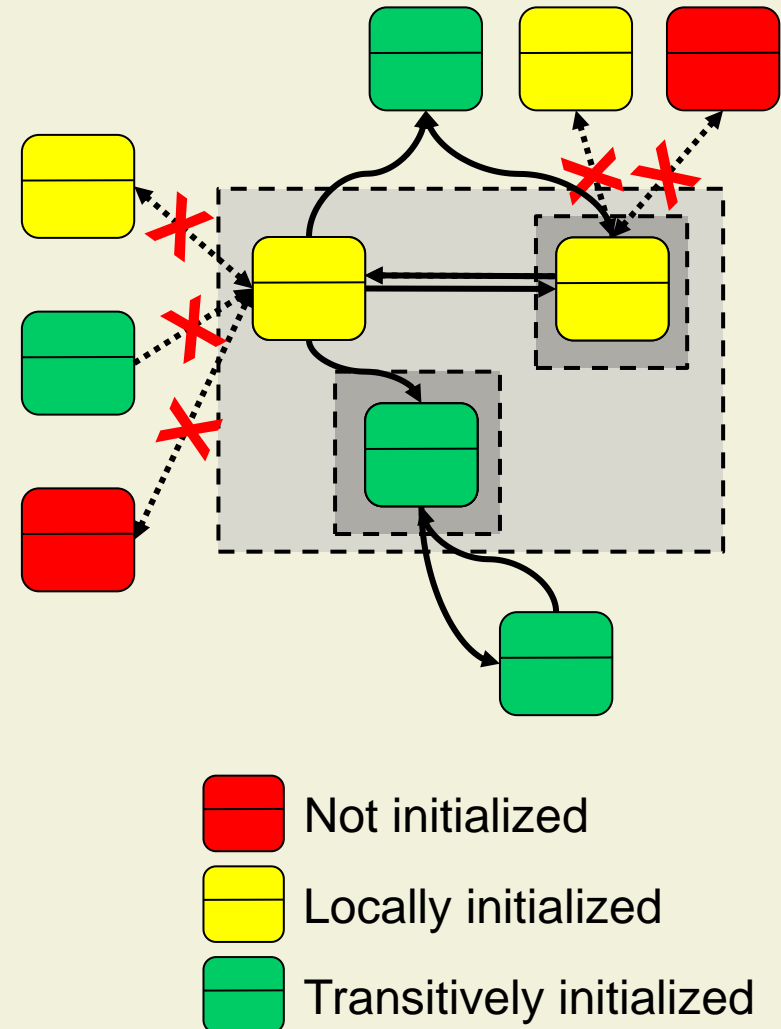
Object Construction

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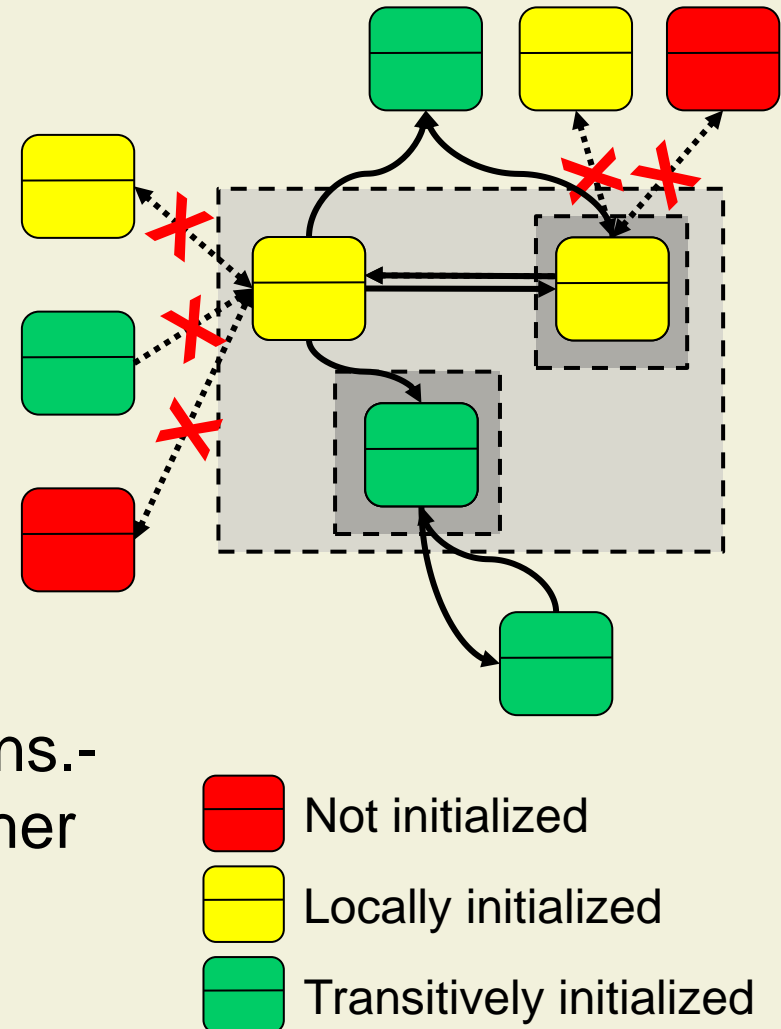
Object Construction

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



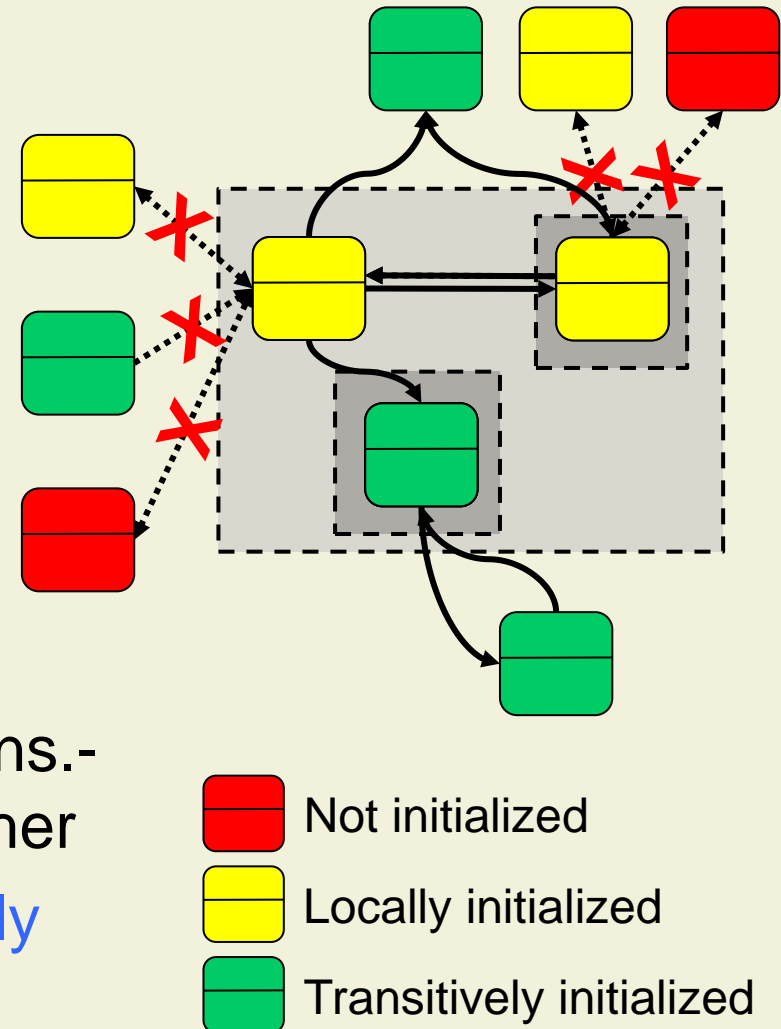
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 - New objects reference only trans.-initialized objects and each other



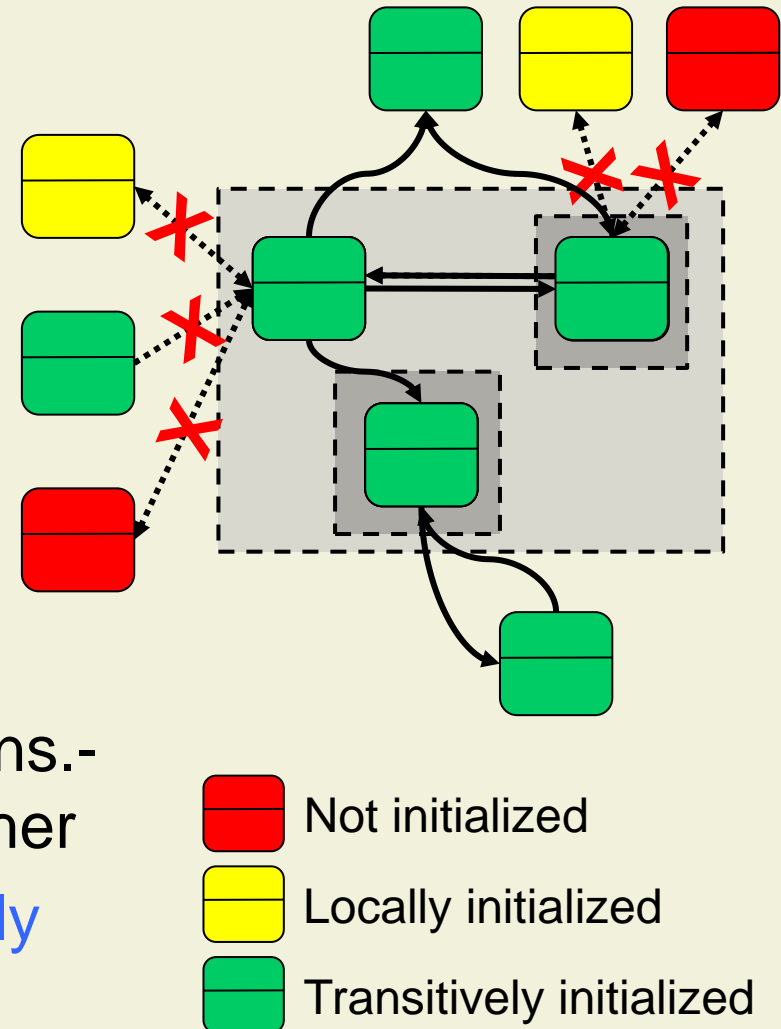
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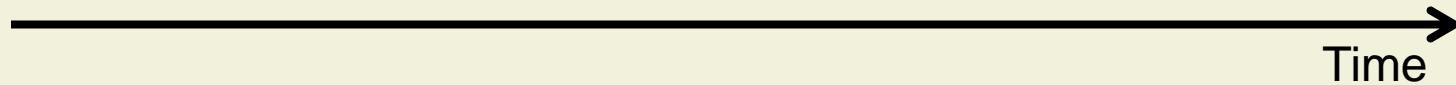


Object Construction

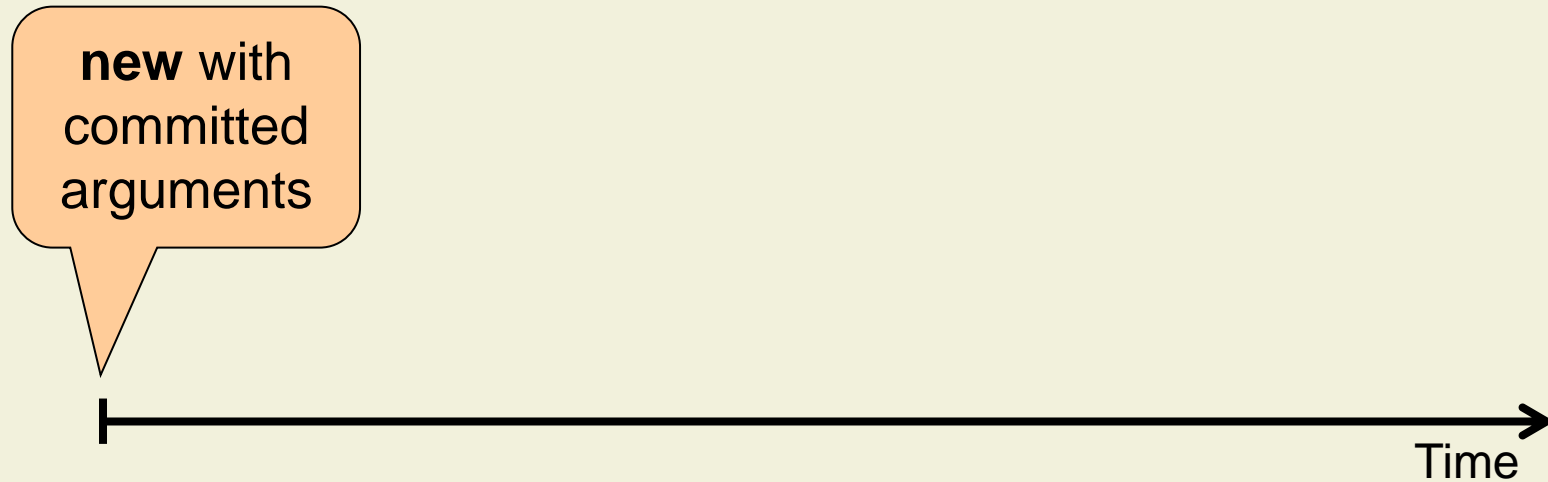
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Completing Object Construction



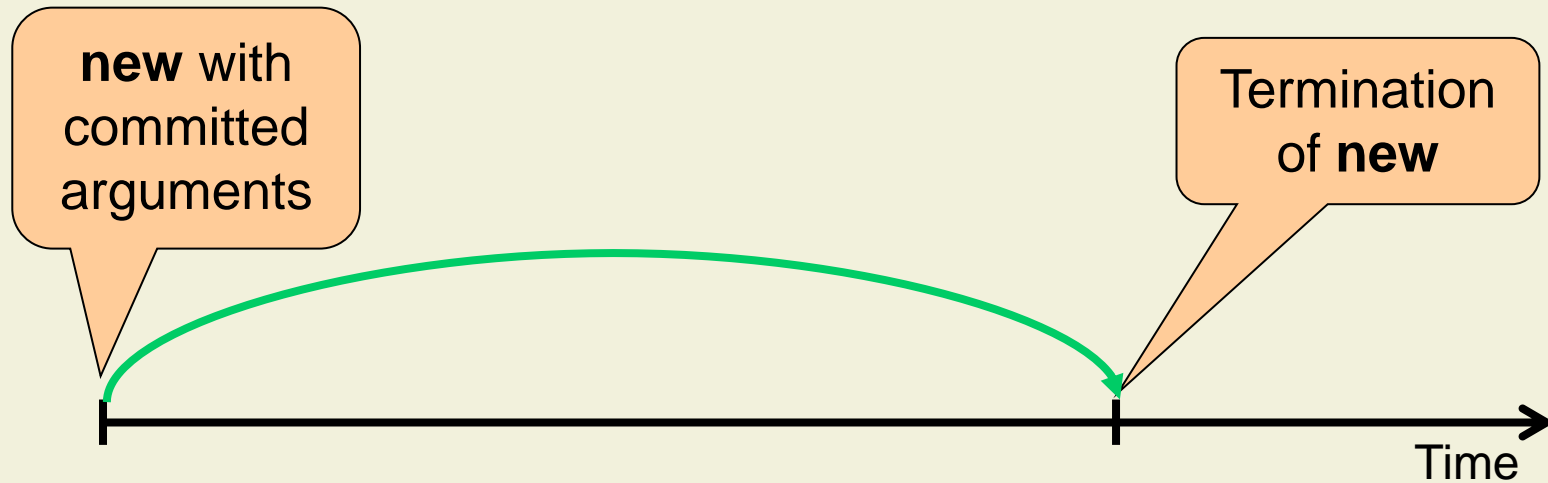
Completing Object Construction



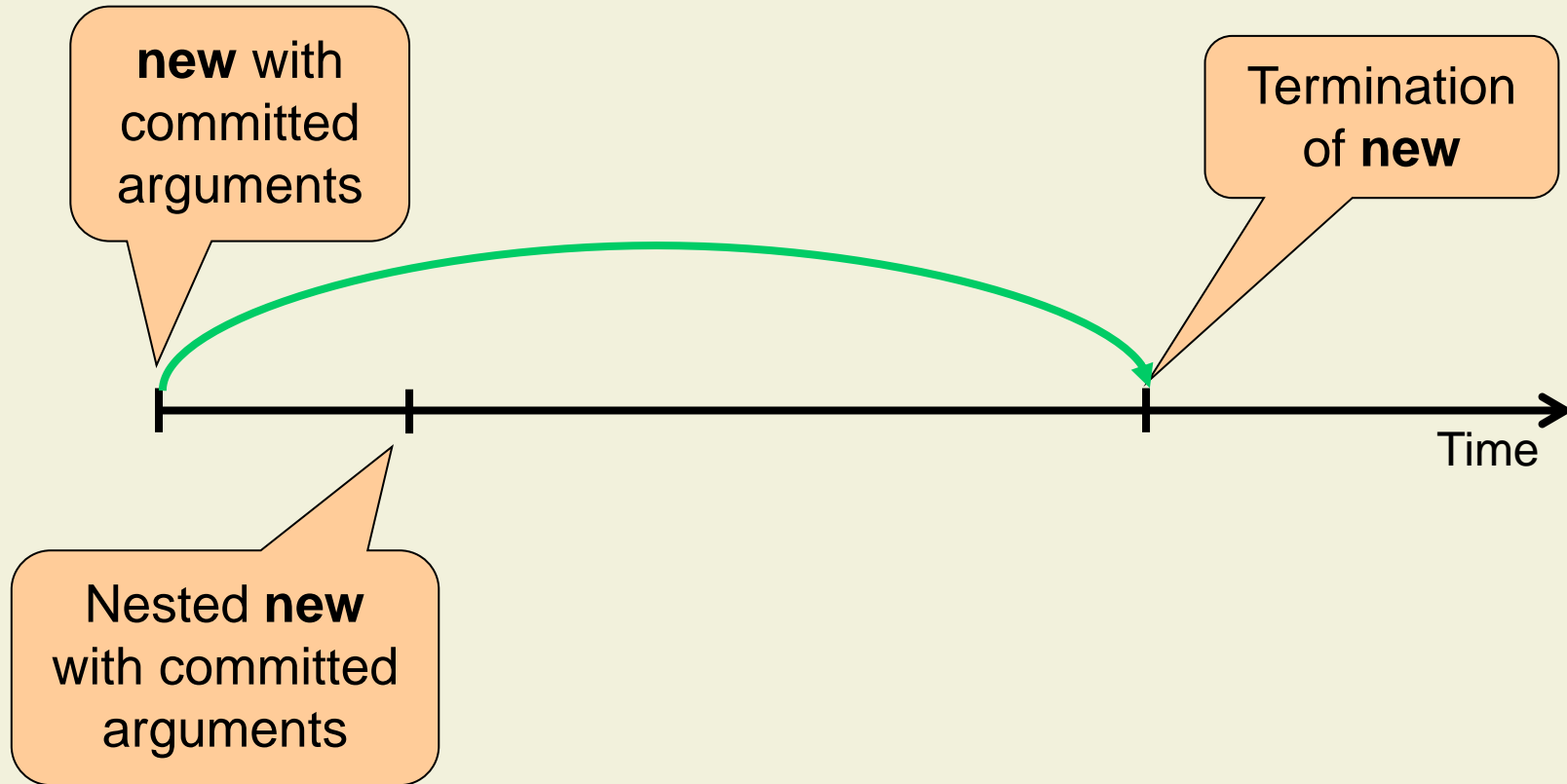
Completing Object Construction



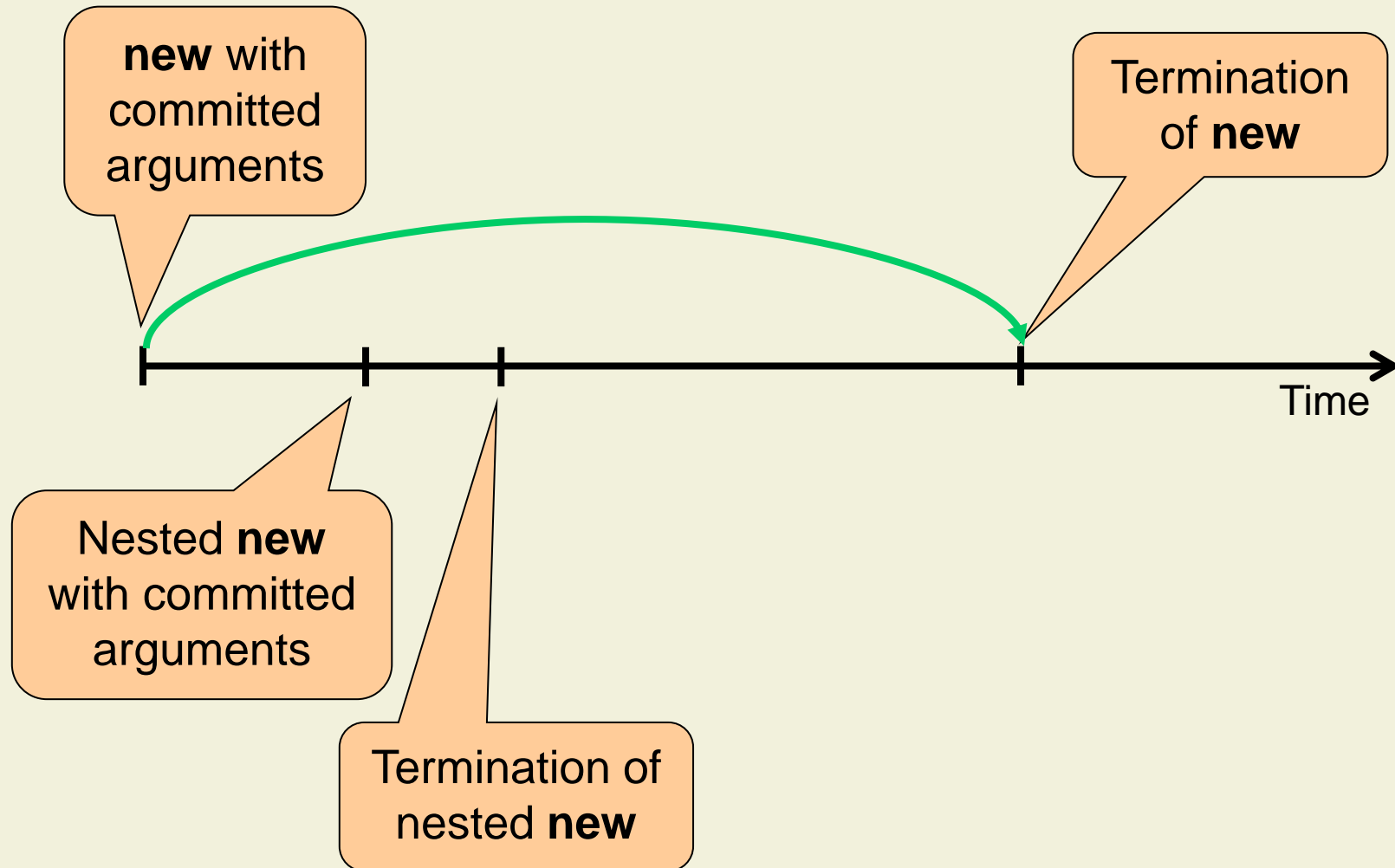
Completing Object Construction



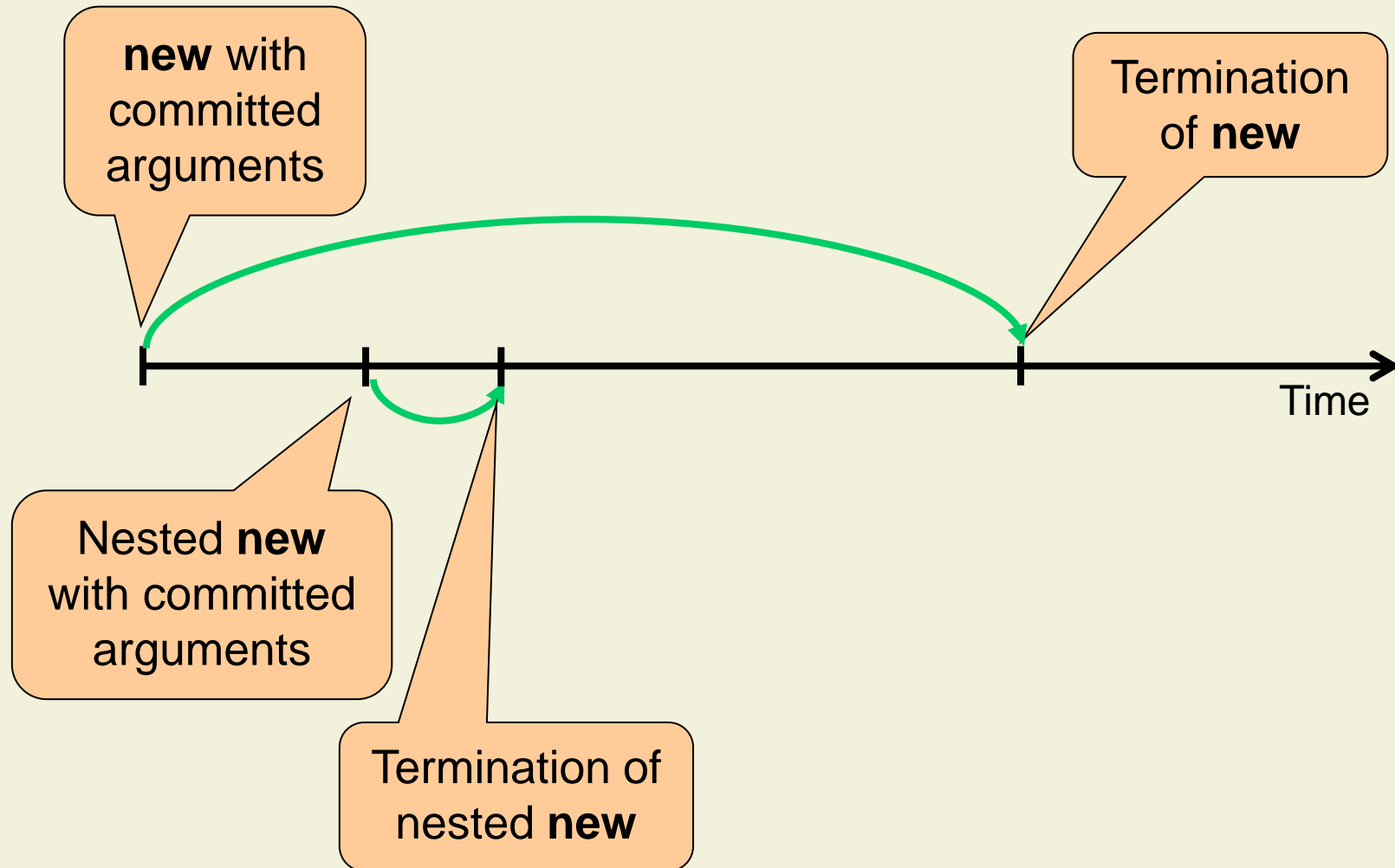
Completing Object Construction



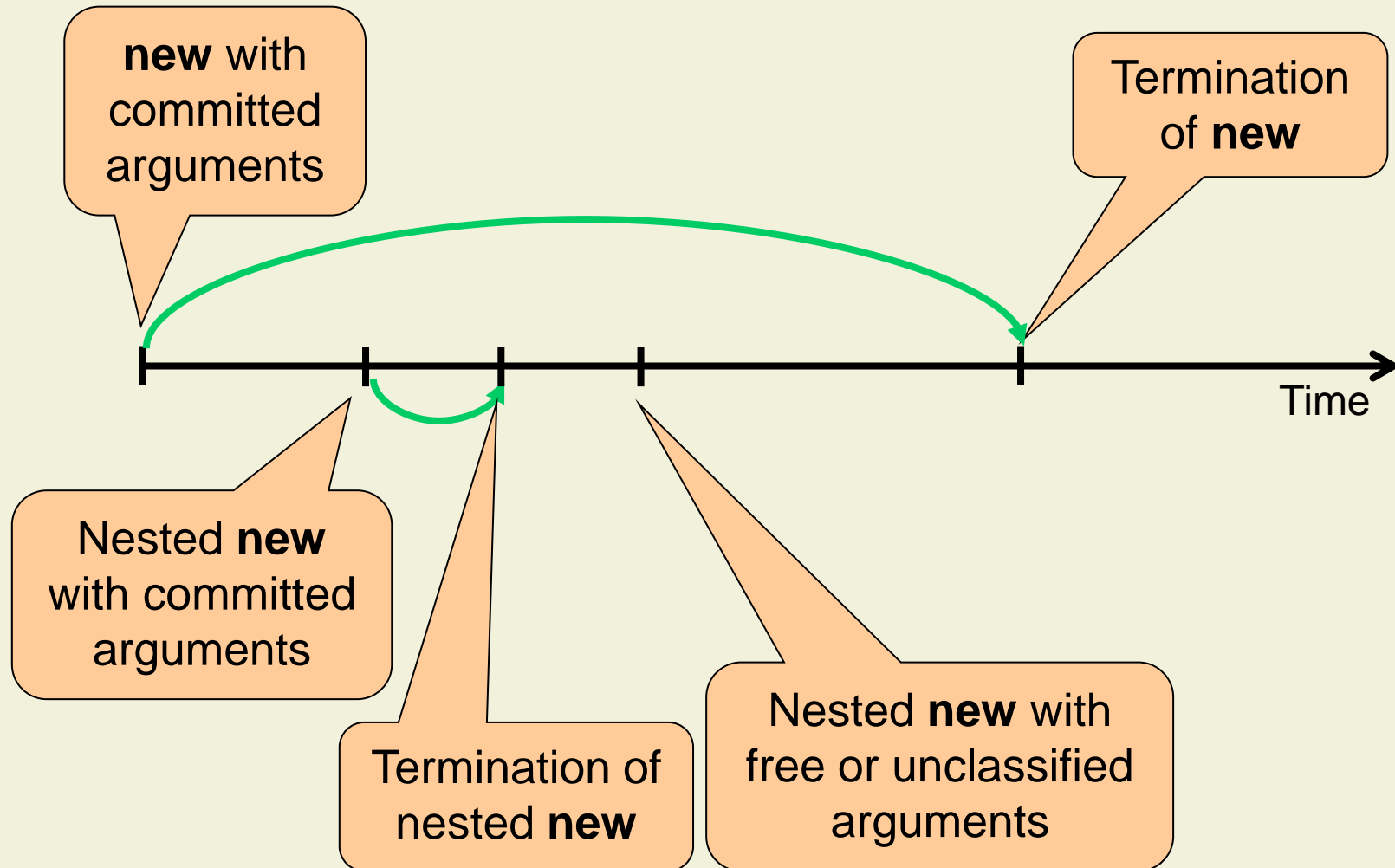
Completing Object Construction



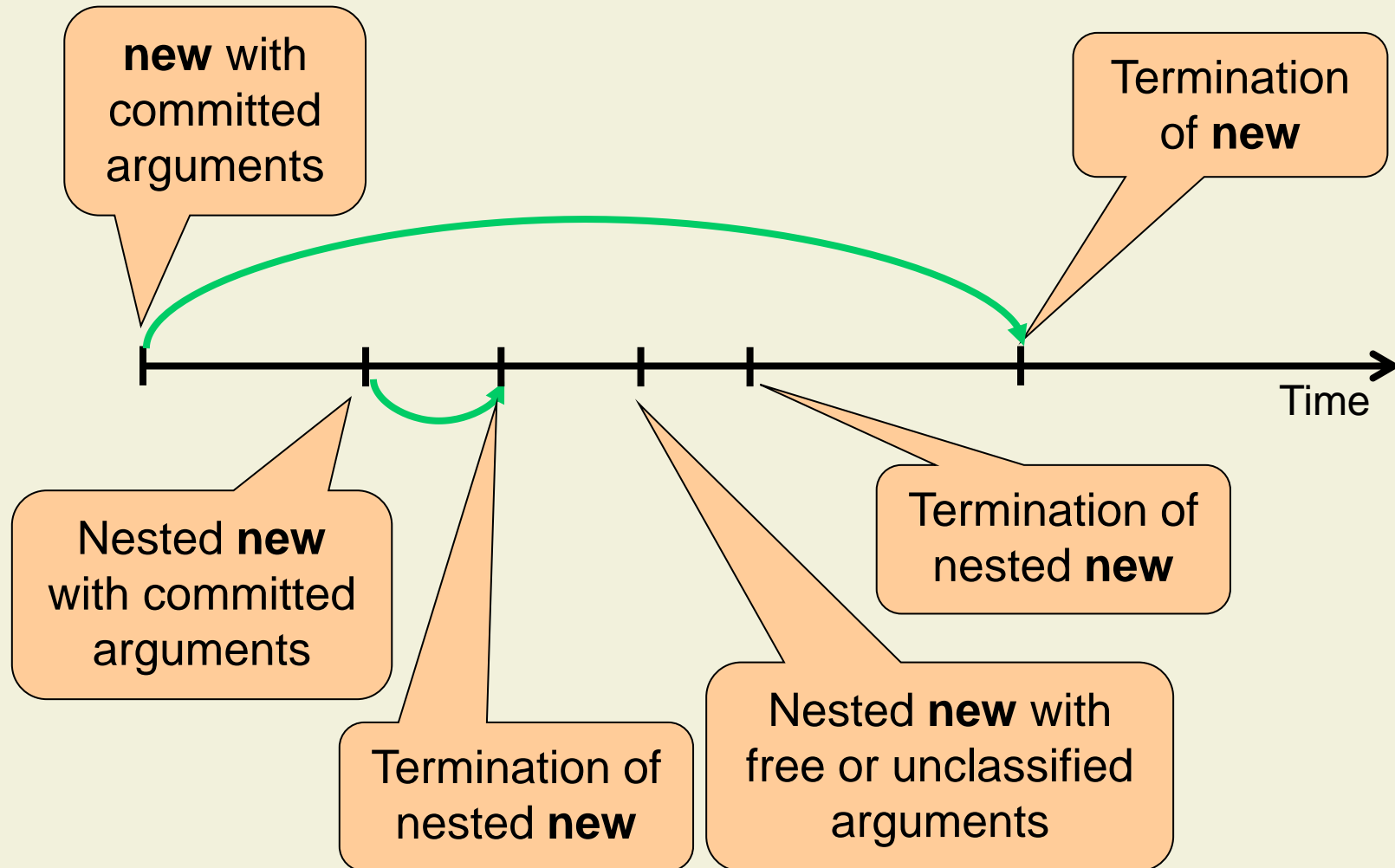
Completing Object Construction



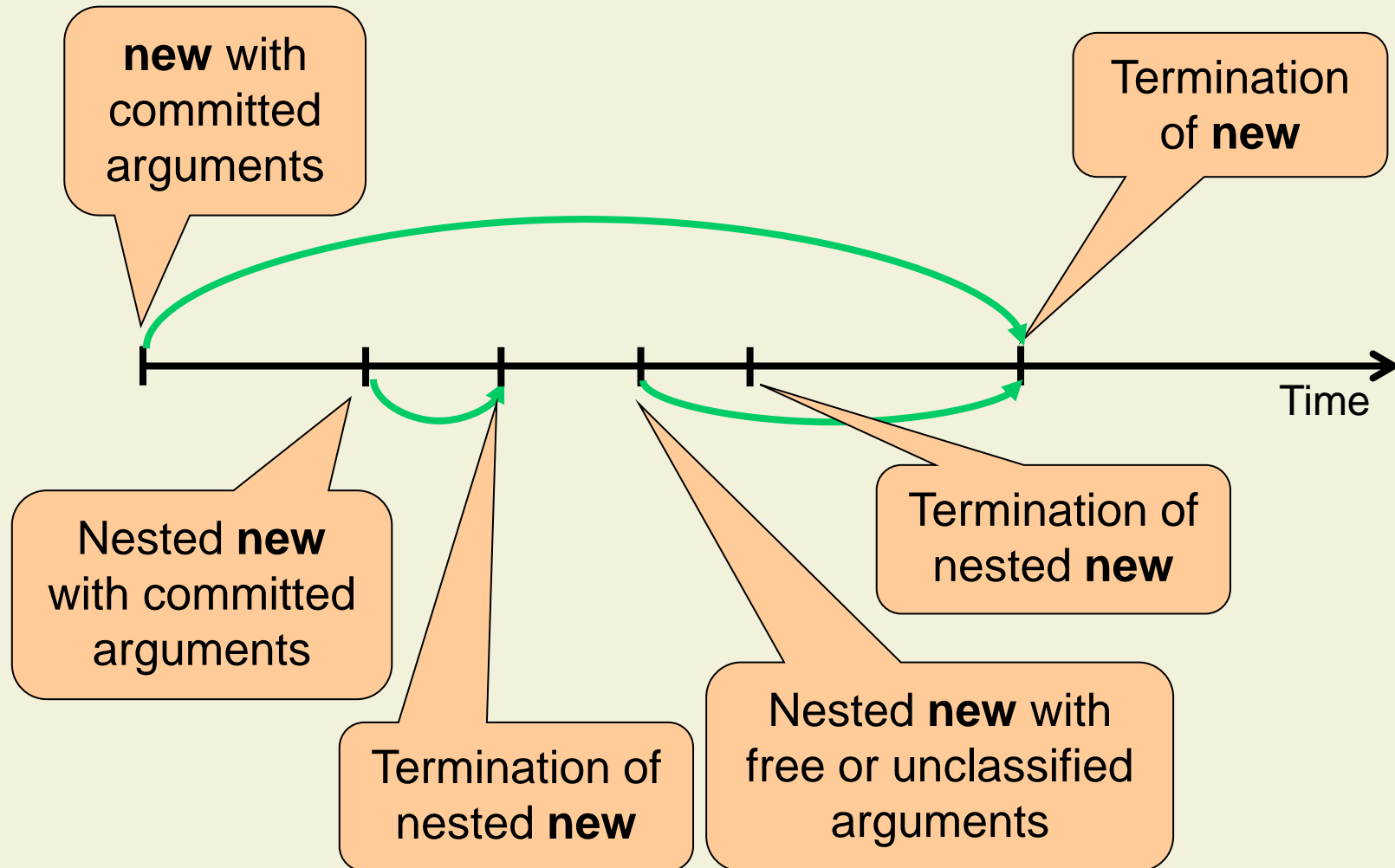
Completing Object Construction



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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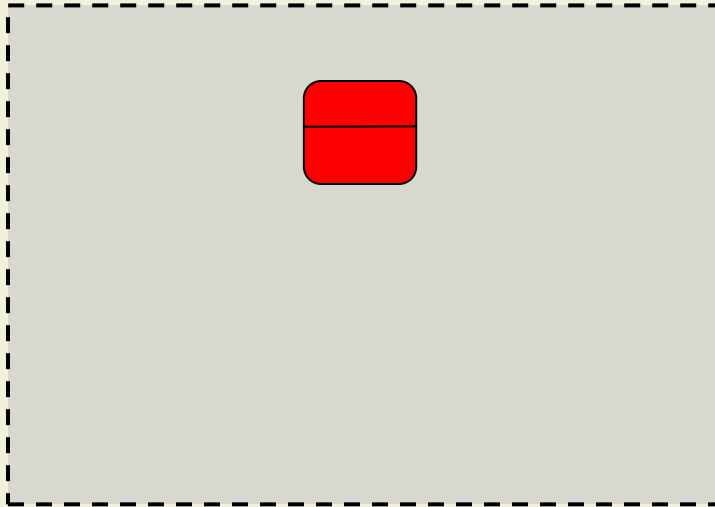
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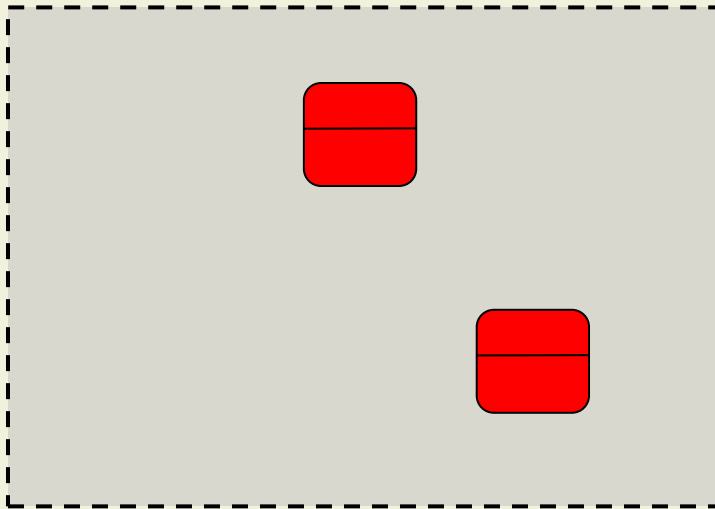
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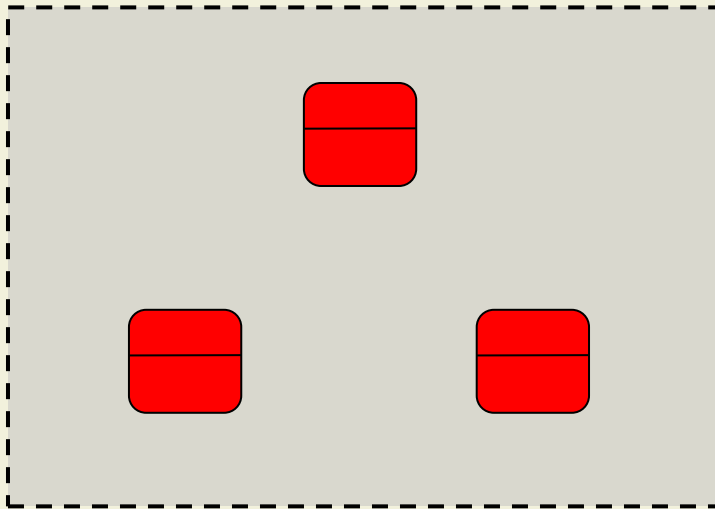
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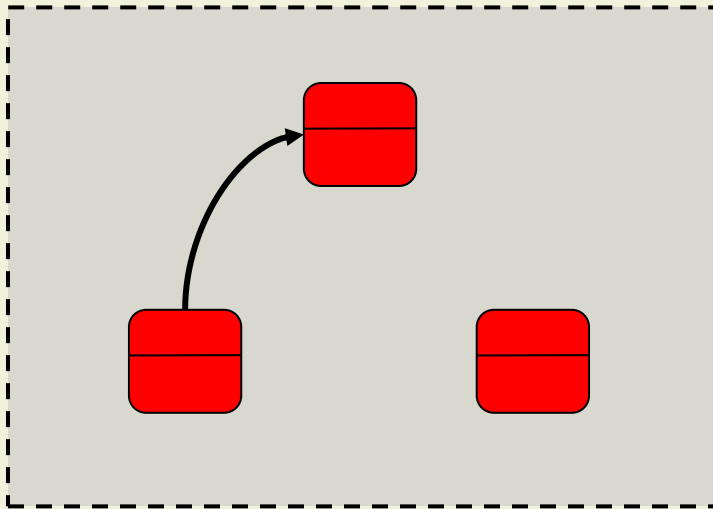
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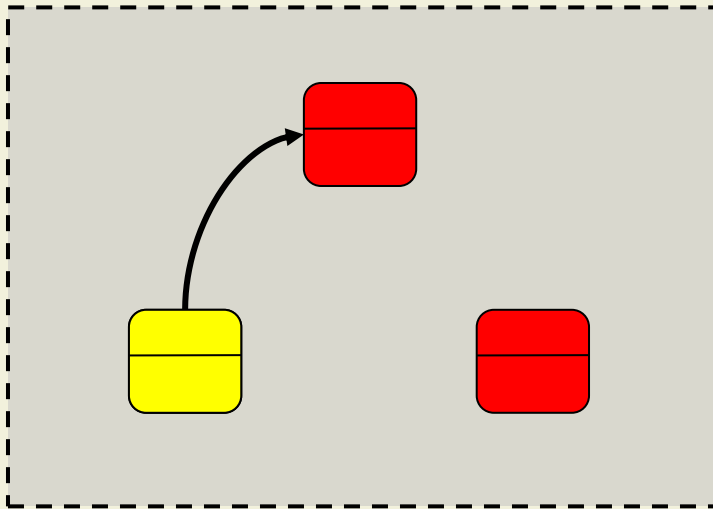
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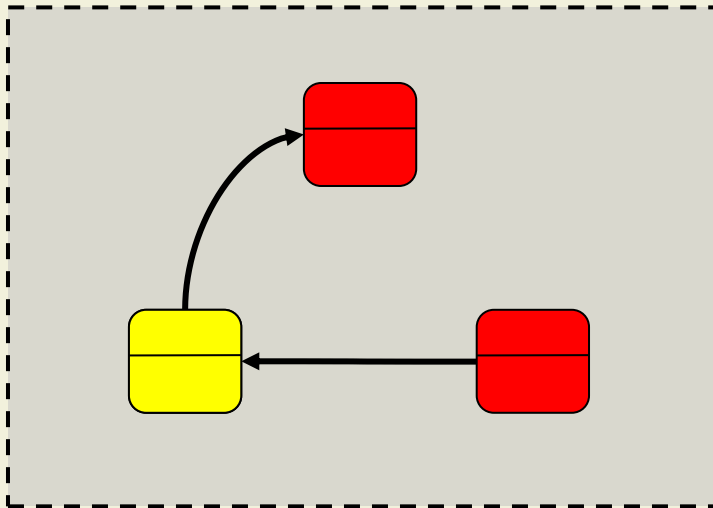
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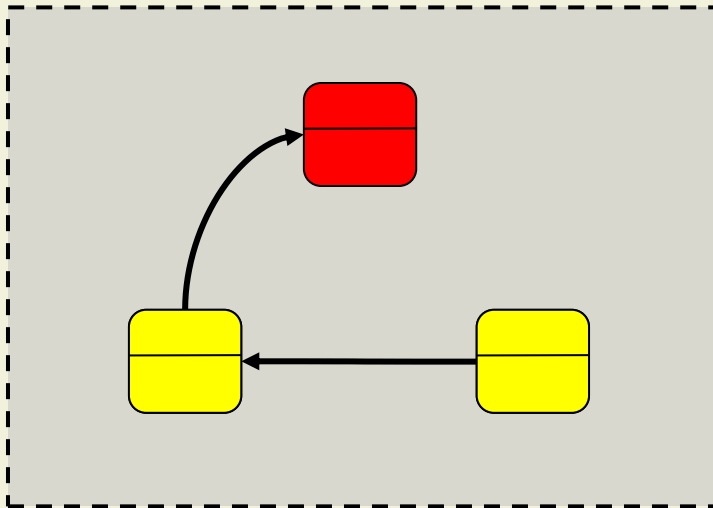
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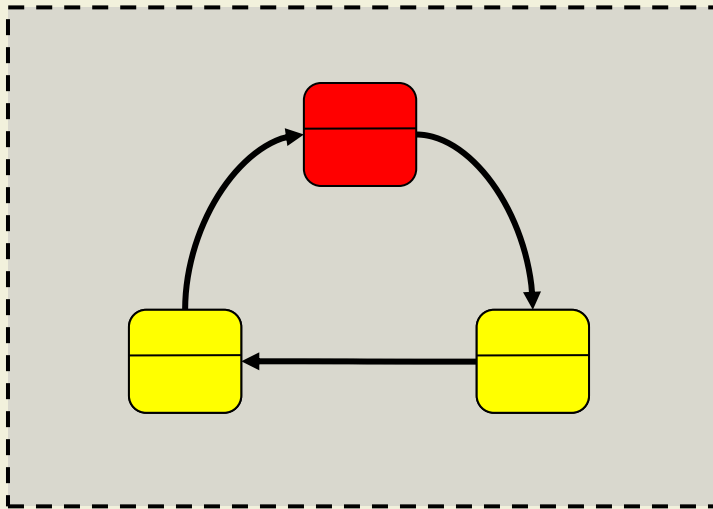
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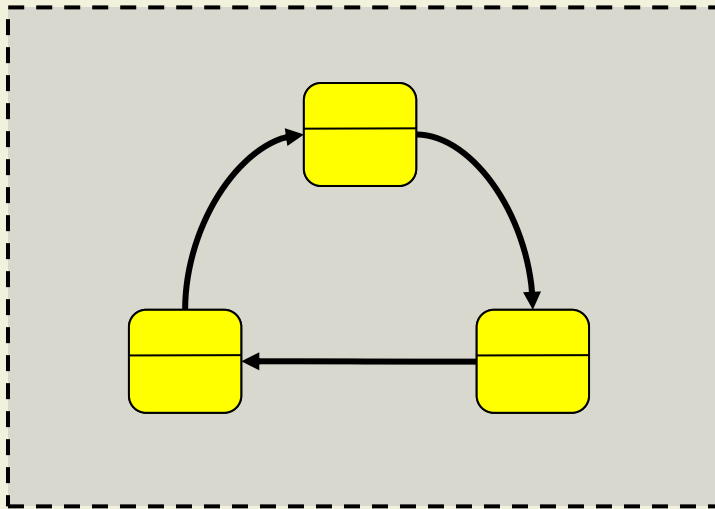
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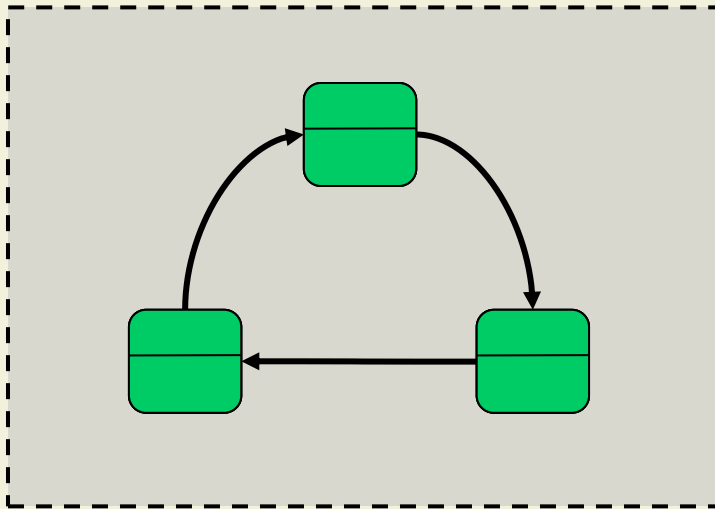
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Problem 1: Method Calls Revisited

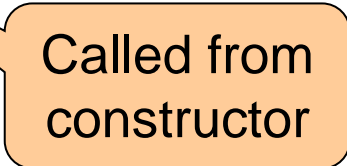
```
class Demo {  
    Vector! cache;  
  
    Demo( ) {  
        int size = optimalSize( );  
        cache = new Vector( size );  
    }  
  
    int optimalSize( ) {  
        return 16;  
    }  
}
```

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

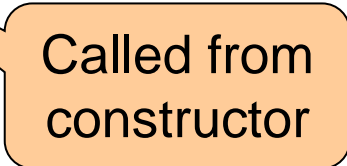


```
class Sub extends Demo {  
    Vector! data;  
  
    Sub( Vector! d ) {  
        data = d.clone( );  
    }  
  
    int optimalSize( ) {  
        return this.data.size( ) * 2;  
    }  
}
```

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

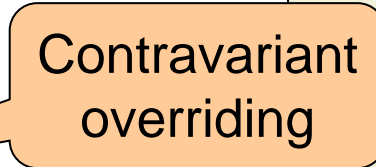
Problem 1: Method Calls Revisited

```
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;  
    }  
}
```



Contravariant overriding

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

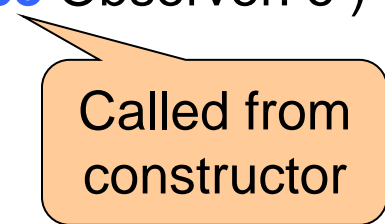
```
Vector! v = new Vector( );  
Sub! s = new Sub( v );
```

Problem 2: Call-backs Revisited

```
class Demo implements Observer {  
    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( 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 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( )
```

Compile-
time error

```
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( ) ... }  
}
```

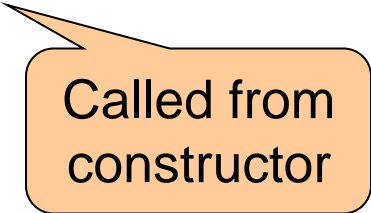
```
class Subject extends Thread {  
    List<Observer!>! list;  
  
    void register( Observer! o )  
    { list.add( o ); }  
  
    void run( ) {  
        while( true ) {  
            if( sensorValueChanged( ) )  
                for( Observer! o: list )  
                    o.update( ... ); 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

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

- Creating objects and initializing their fields is time consuming
 - Long application start-up time
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Not initialized by constructor

```
class Demo {  
    private Vector? data;  
  
    Demo( ) {  
        // do not initialize data  
    }  
  
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        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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```
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
 - Both can be non-null or possibly-null

Non-null array with
non-null elements

```
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 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

Non-null array with
non-null elements

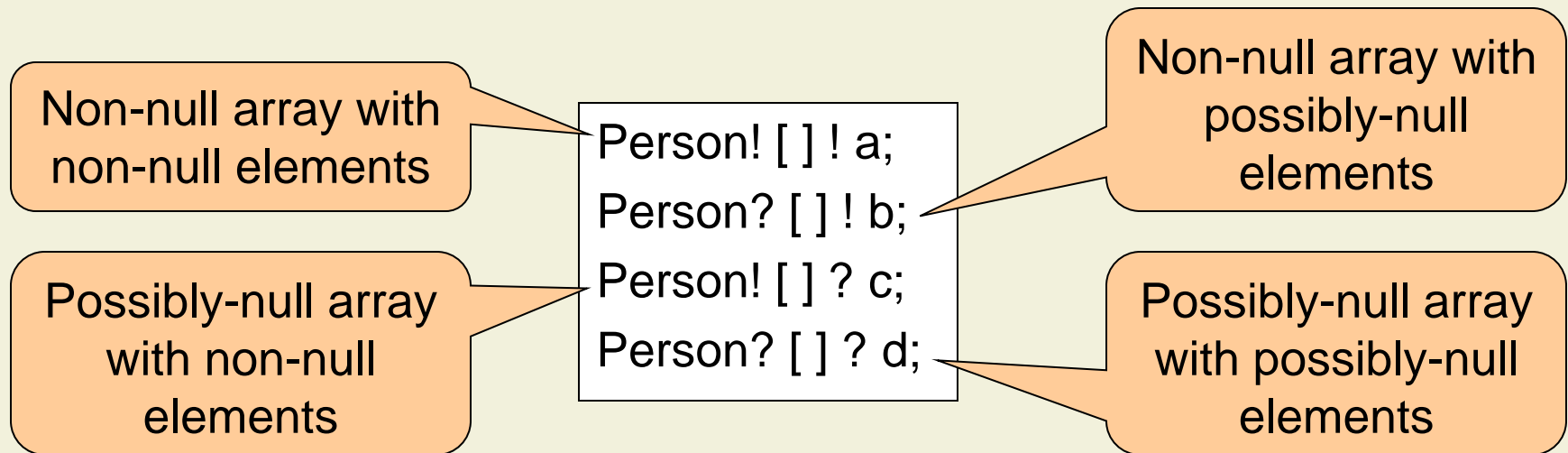
Possibly-null array
with non-null
elements

```
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
 - Arrays are typically initialized using loops
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- 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";  
        }  
    }  
}
```

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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```
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";  
        }  
    }  
}
```

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

```
free 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

```
free 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

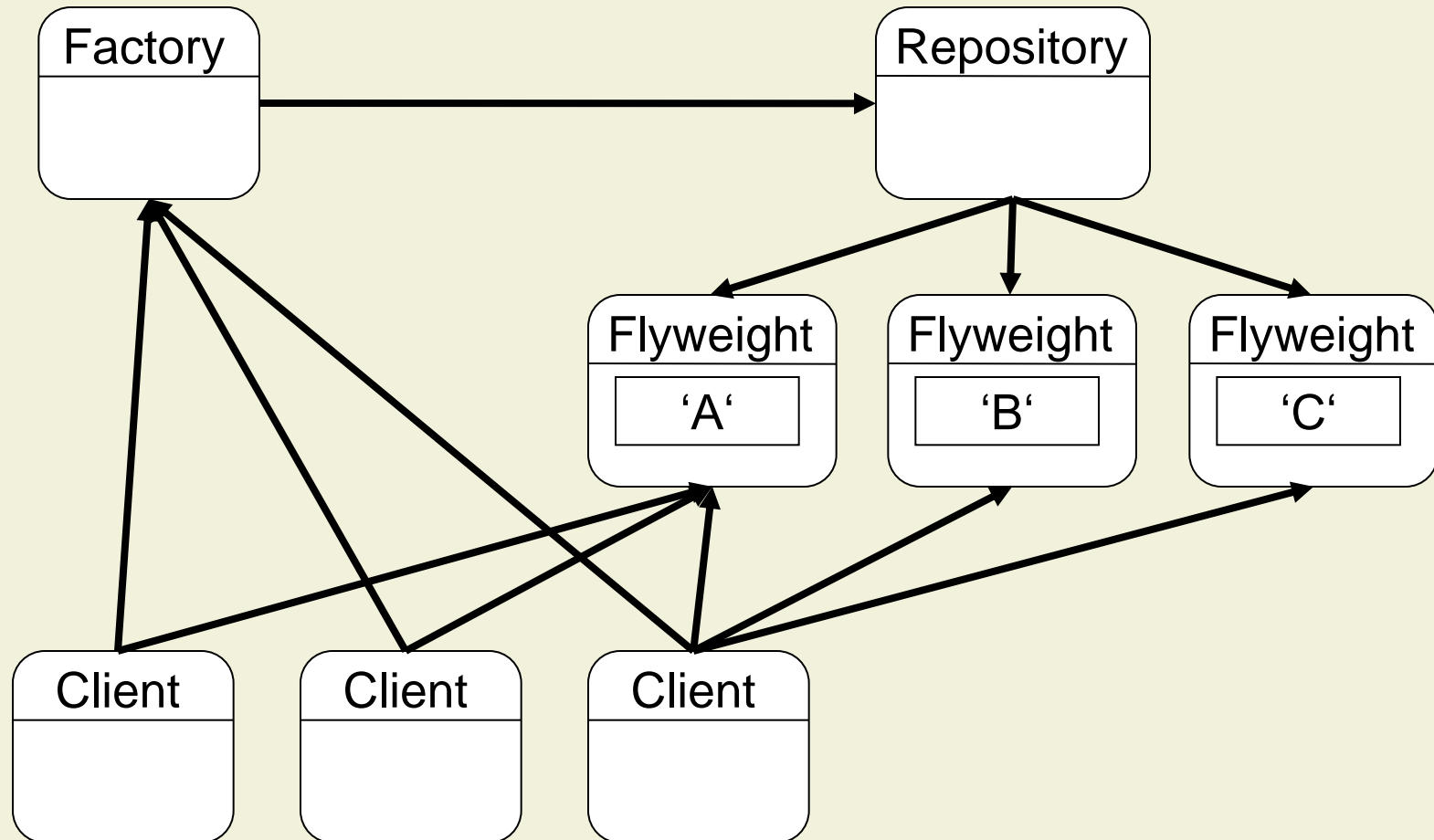
7. Initialization

7.1 Simple Non-Null Types

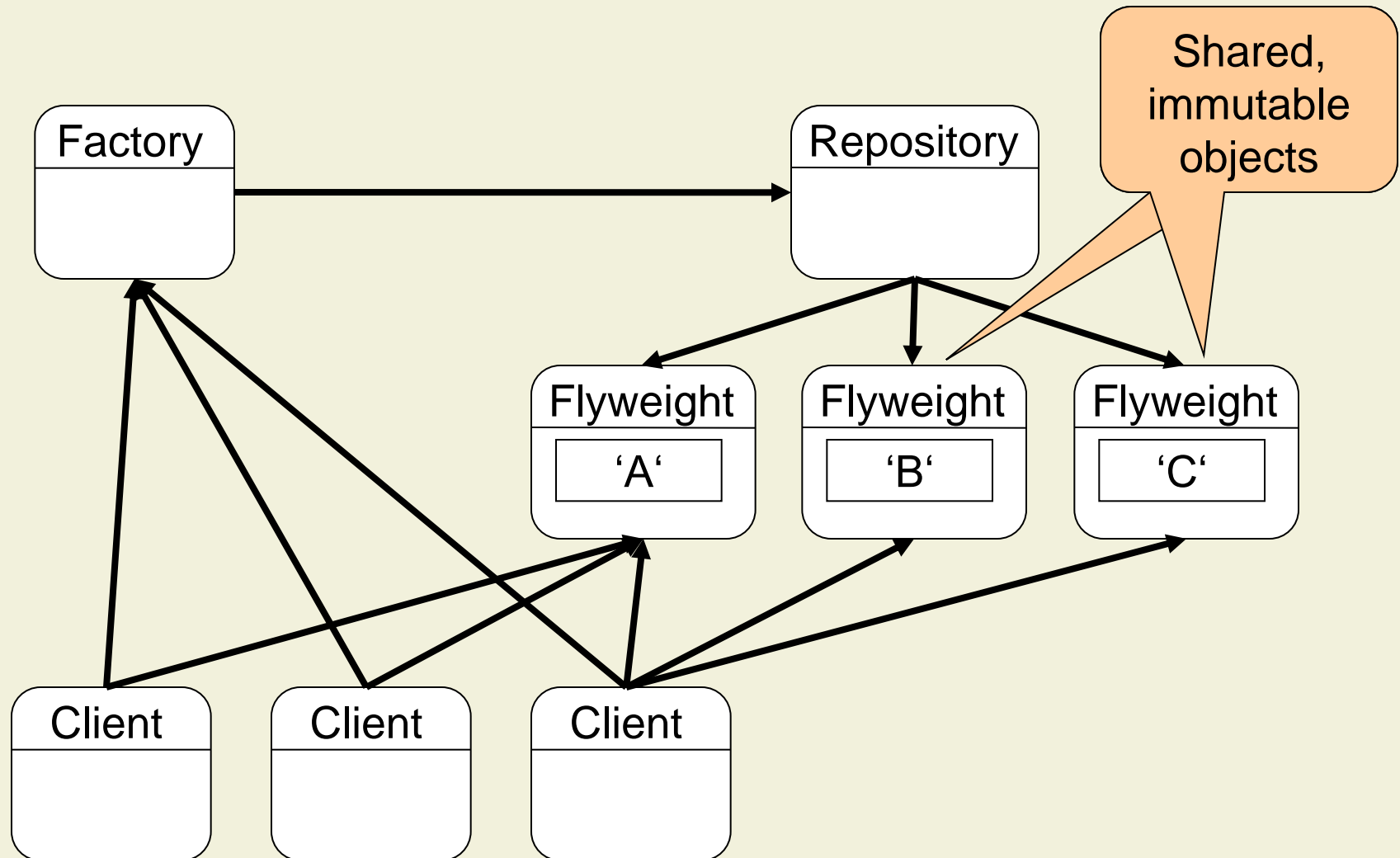
7.2 Object Initialization

7.3 Initialization of Global Data

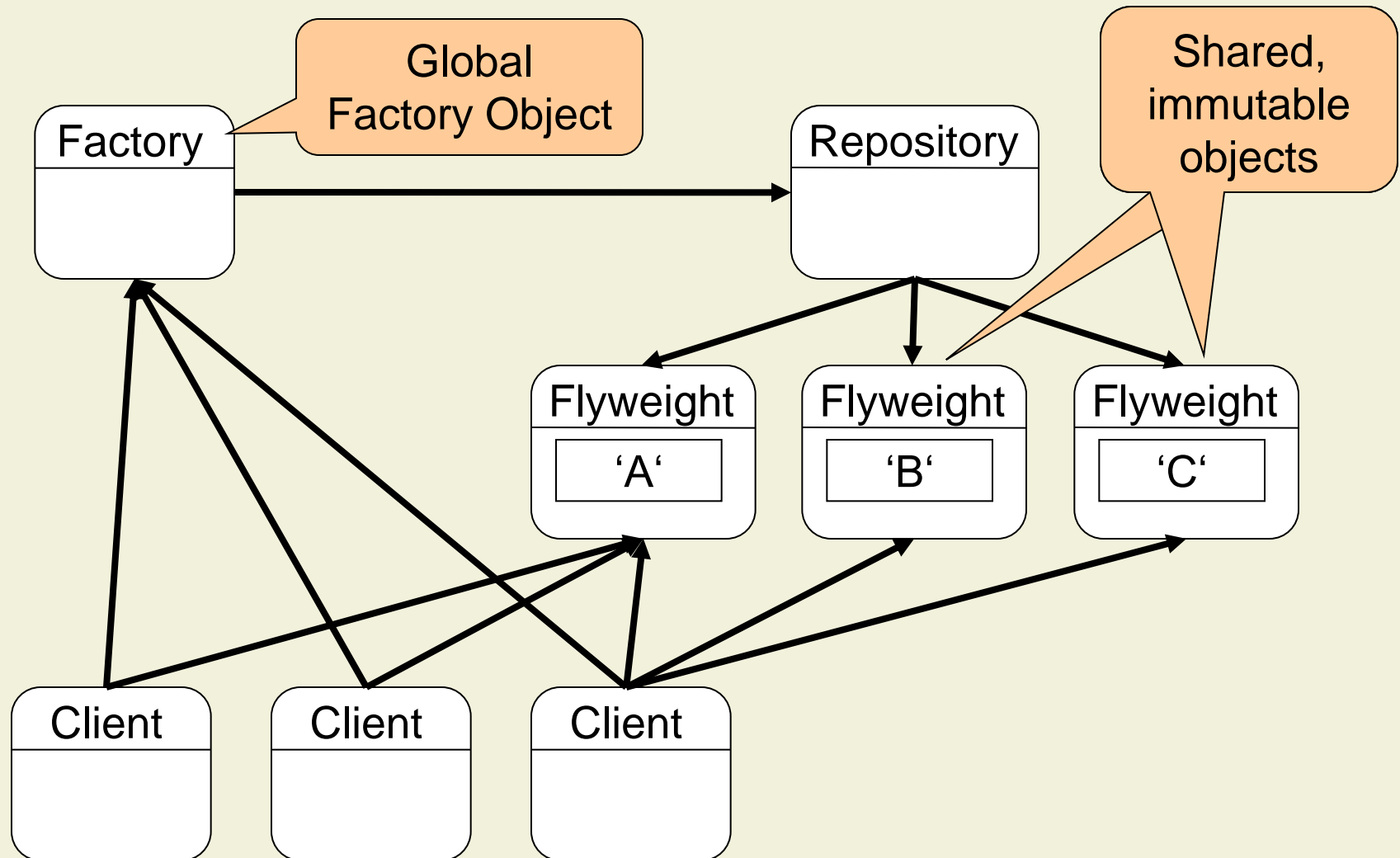
The Flyweight Pattern



The Flyweight Pattern

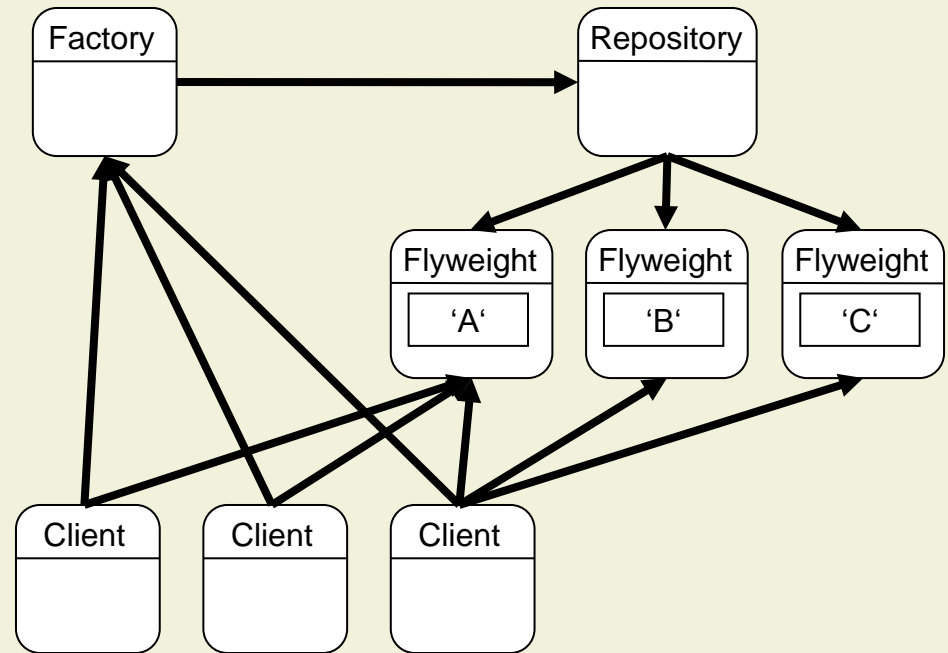


The Flyweight Pattern



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

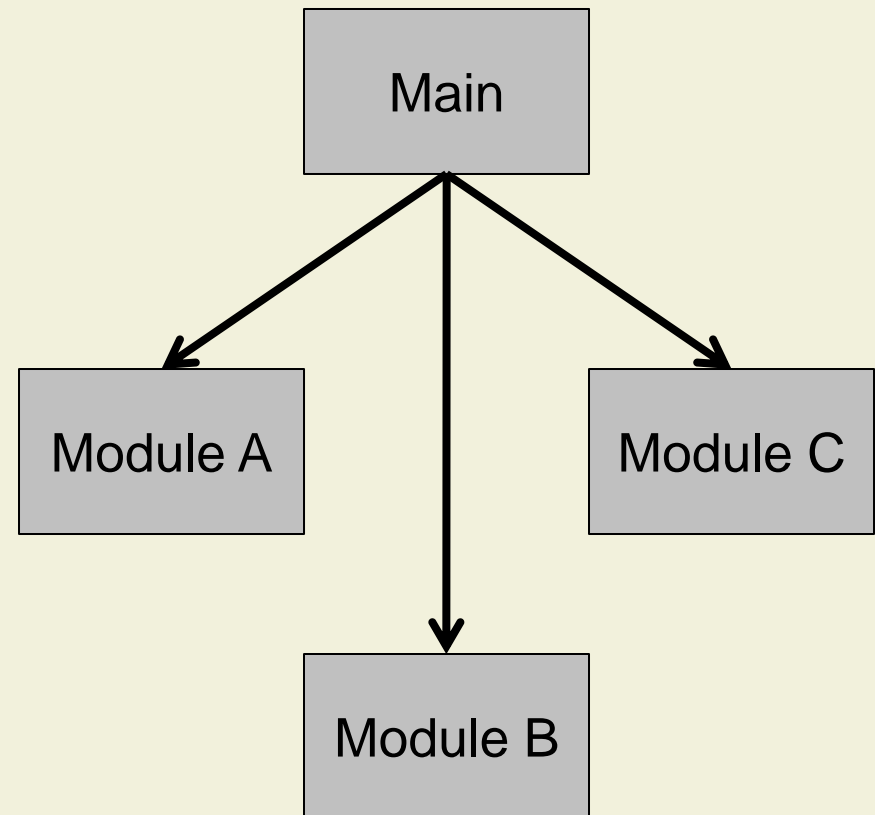
- **Global variables**
store references to
global data
- Initialization is done
by **explicit calls** to
init-methods

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

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

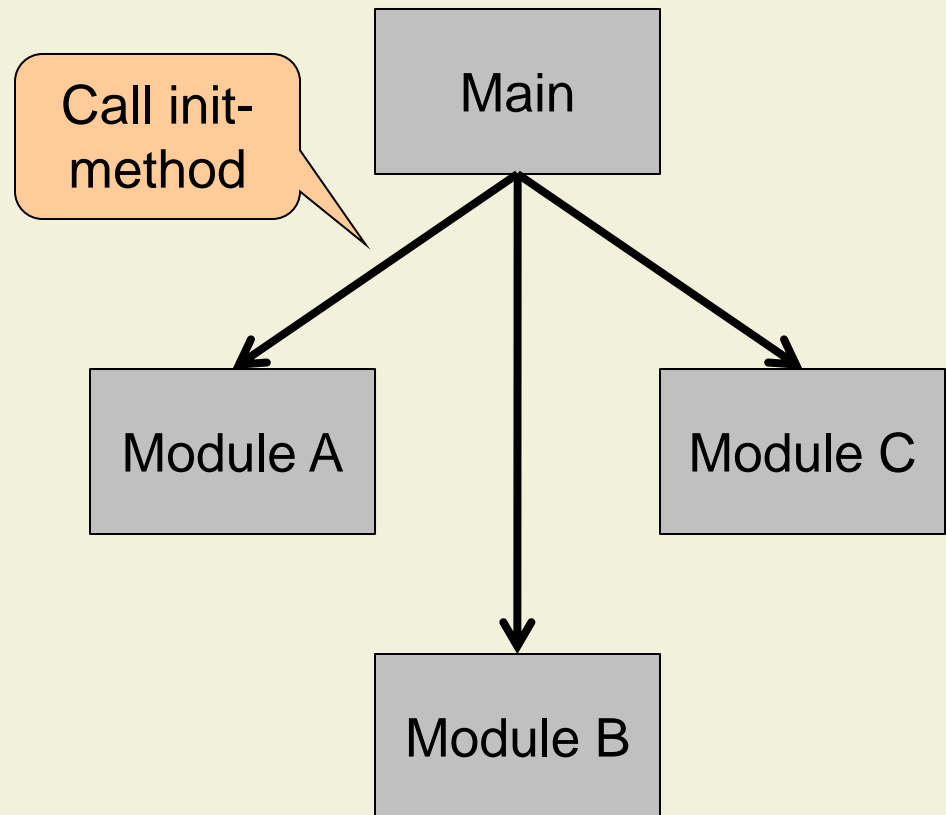

Globals and Init-Methods: Dependencies

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



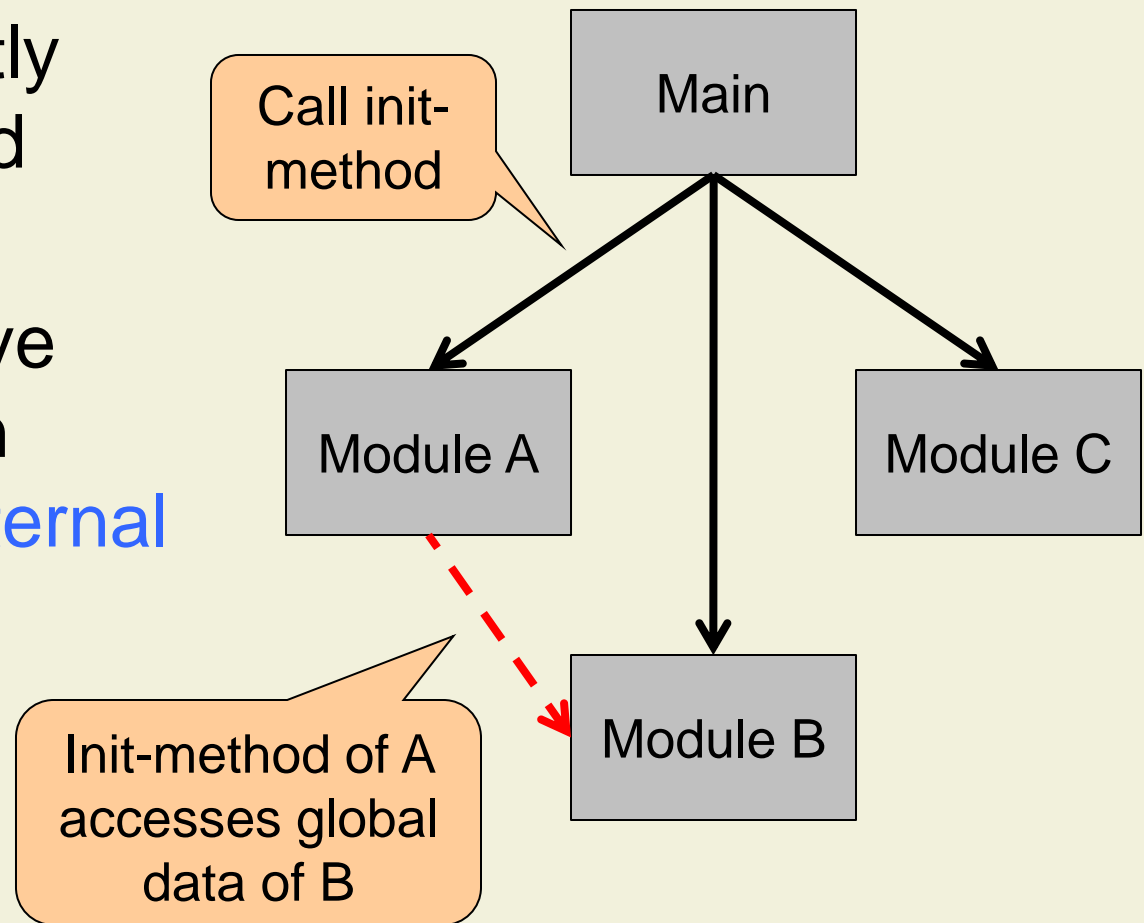
Globals and Init-Methods: Dependencies

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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

- A class C's static initializer runs **immediately before first**
 - Creation of a C-instance
 - Call to a static method of C
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- 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++;  
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}
```

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

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```

Initialize
UniqueID

Initialize
Debug

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

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

Static Initializers: Mutual Dependencies

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        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