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

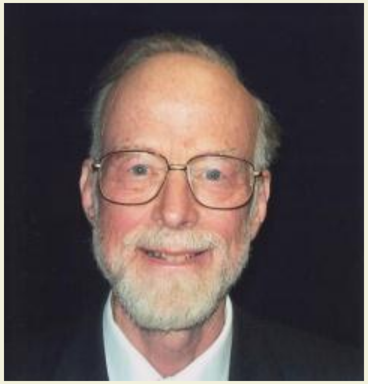
Highly Dynamic Execution Model

→ 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

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;

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

Most variables hold non-null values

```
  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

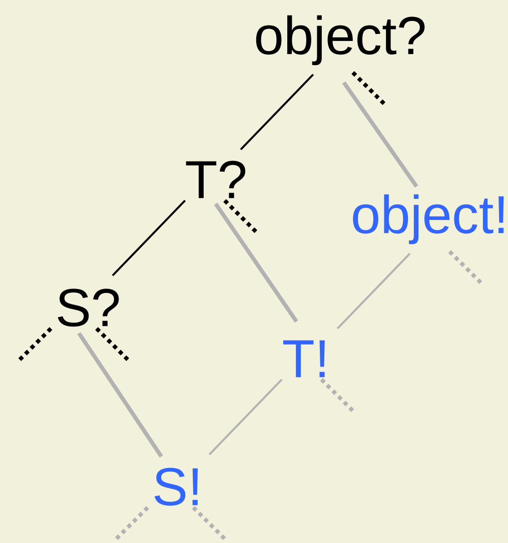
Subtyping and Casts

- The values of a type T! are a proper subset of T?
  - S! <: T!
  - S? <: T?
  - T! <: T?
- 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( );
```

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 );
  }
}
```

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

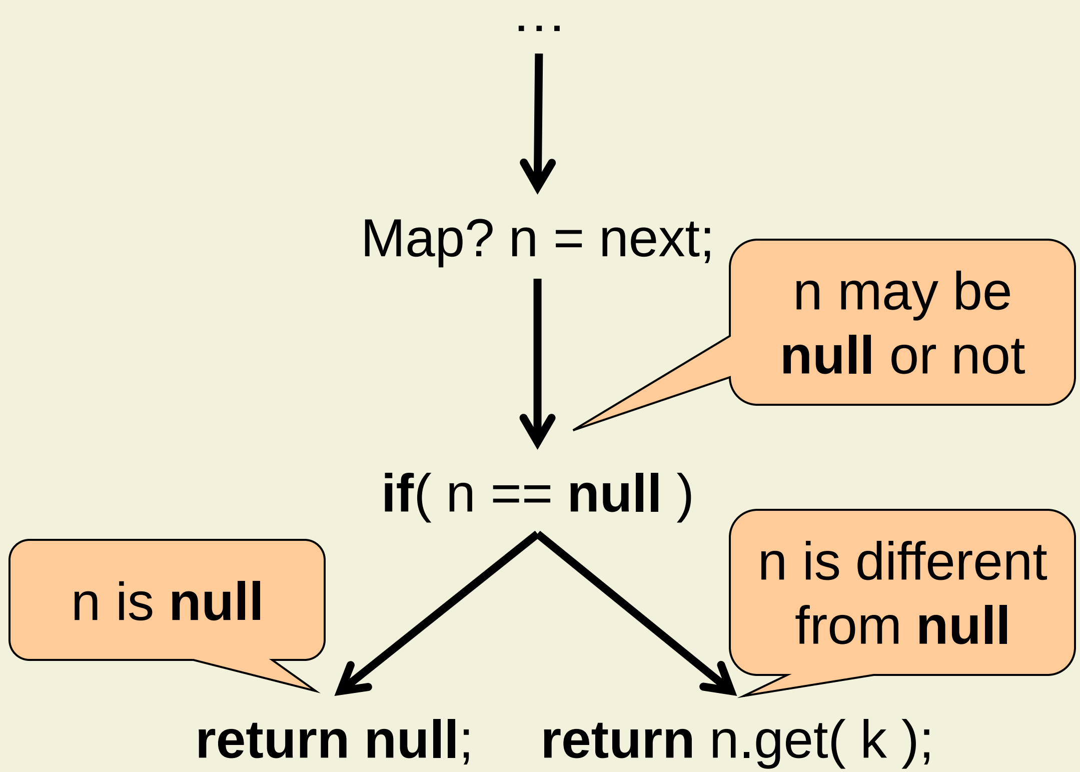
- *Data-flow analysis is a technique for gathering information about the possible set of values calculated at various points in a computer program. A program's control flow graph is used to determine those parts of a program to which a particular value assigned to a variable might propagate.* [Wikipedia]

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 );
  }
}
```

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 (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

7. Initialization

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**

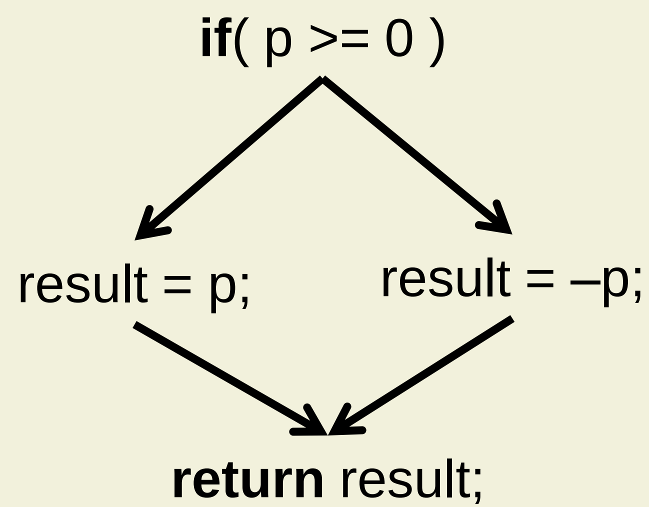
Type invariant is violated here!

- 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

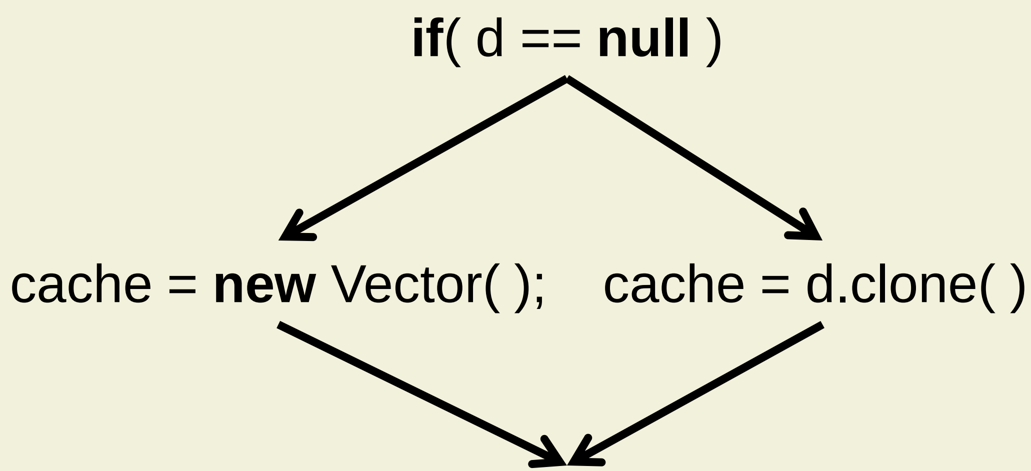
```
int abs( int p ) {
  int result;
  if( p >= 0 )  result = p;
  else  result = –p;
  return result;
}
```



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;
  }
}
```

Dynamically bound

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

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

  int optimalSize( ) {
    return data.size( ) * 2;
  }
}
```

Implicit super-call

NullPointer Exception

```
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( … );
  }
}
```

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 );
```

NullPointer Exception

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( ) … }
}
```

NullPointer Exception

```
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

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;
  }
}
```

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 );
    }
  }
  …
}
```

NullPointer Exception

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 cyclic list
  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

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

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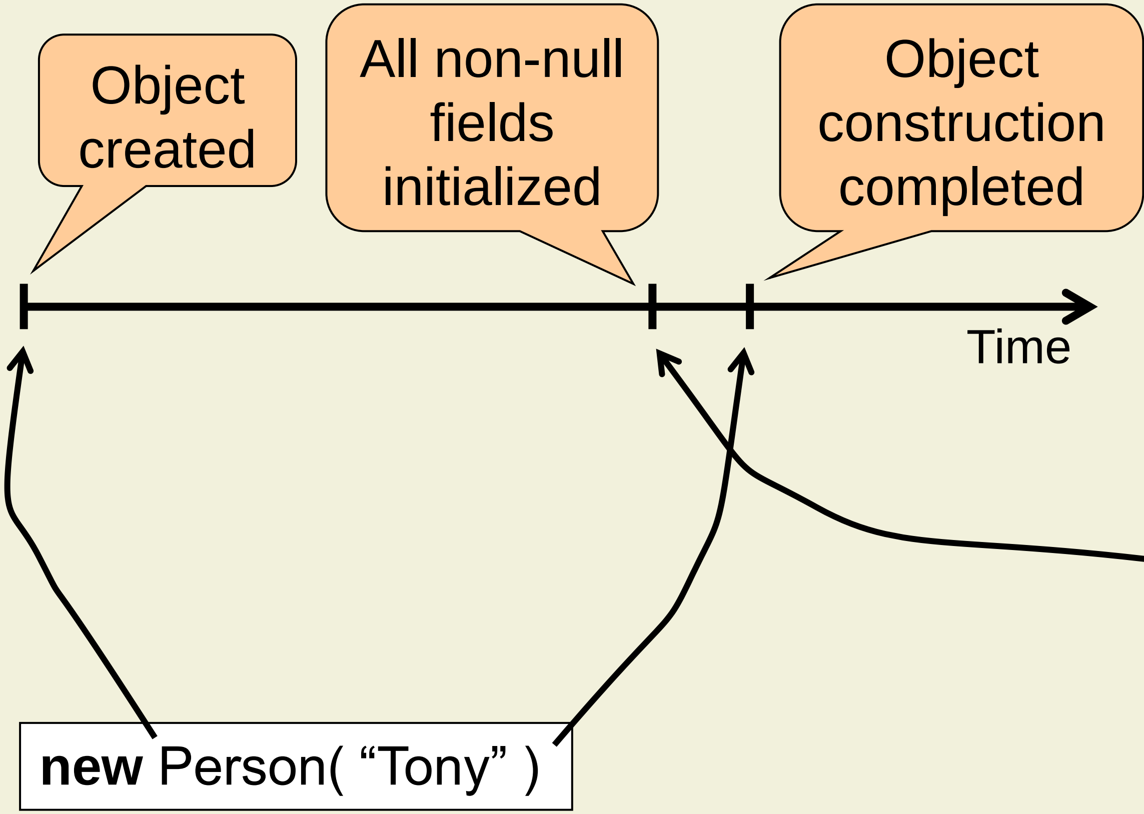
Initialization Phases




```
final class Person {
  String! name;
  static int count;

  Person( String! name ) {
    this.name = name;
    Person.count++;
  }
}
```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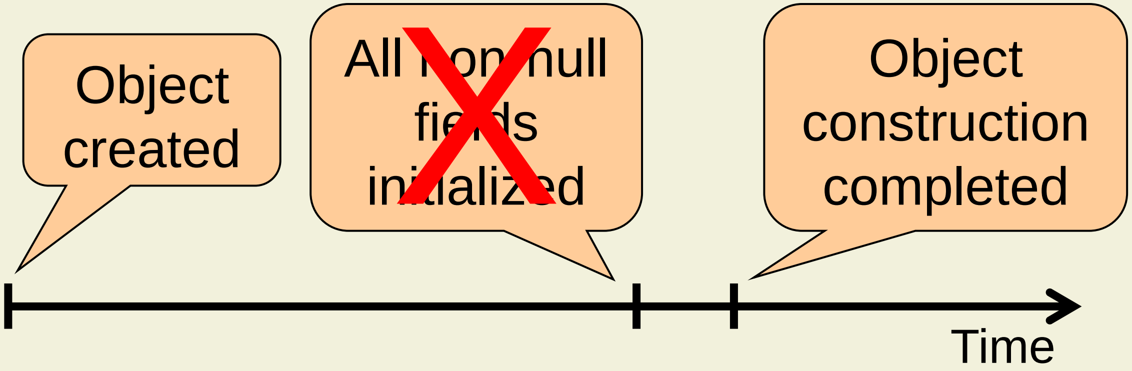
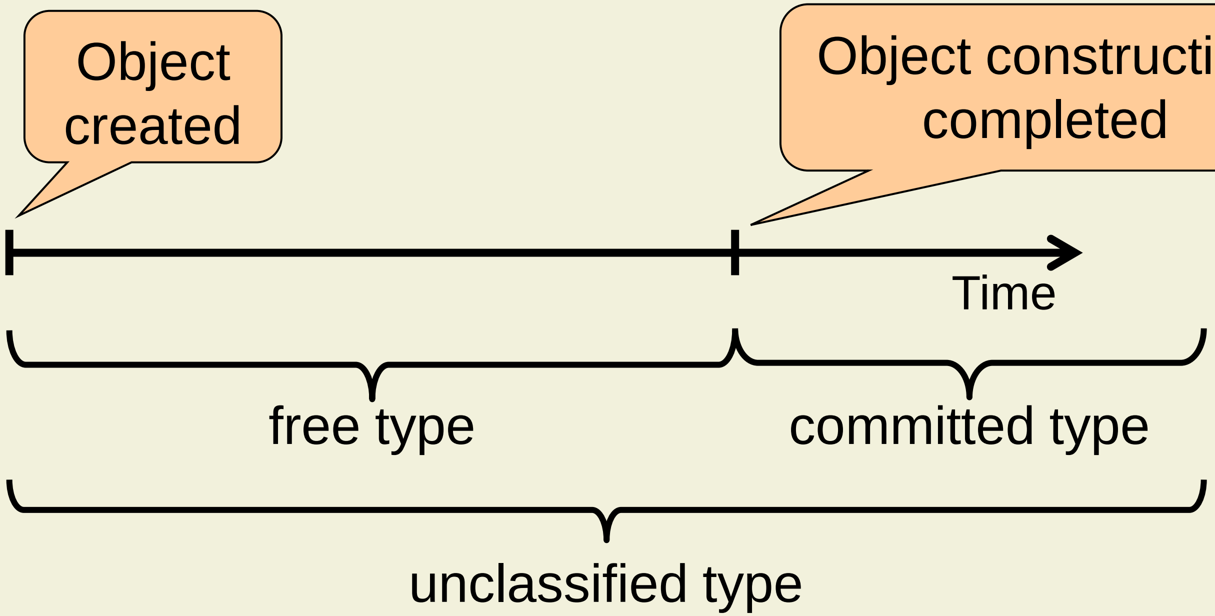
Tracking Object Construction



- 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! cT = …	uT = cT;	fT = cT;
free T! fT = …	uT = fT;	cT = (T!) uT;
unc T? uT = …	**unc** T! nT = (**unc** T!) uT;	fT = (**free** T!) uT;

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	?	?

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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;
  }
}
```

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

this is free inside constructor

Object referenced by **this**.id has finished construction

Parameter s is committed by default

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

Type of e_1	committed	free	unc
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

Type of e	T!	T?
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
- 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 );
  }
}
```

name is of a committed type

this is of a free type

Definite assignment check succeeds

Non-nullness invariant is satisfied

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

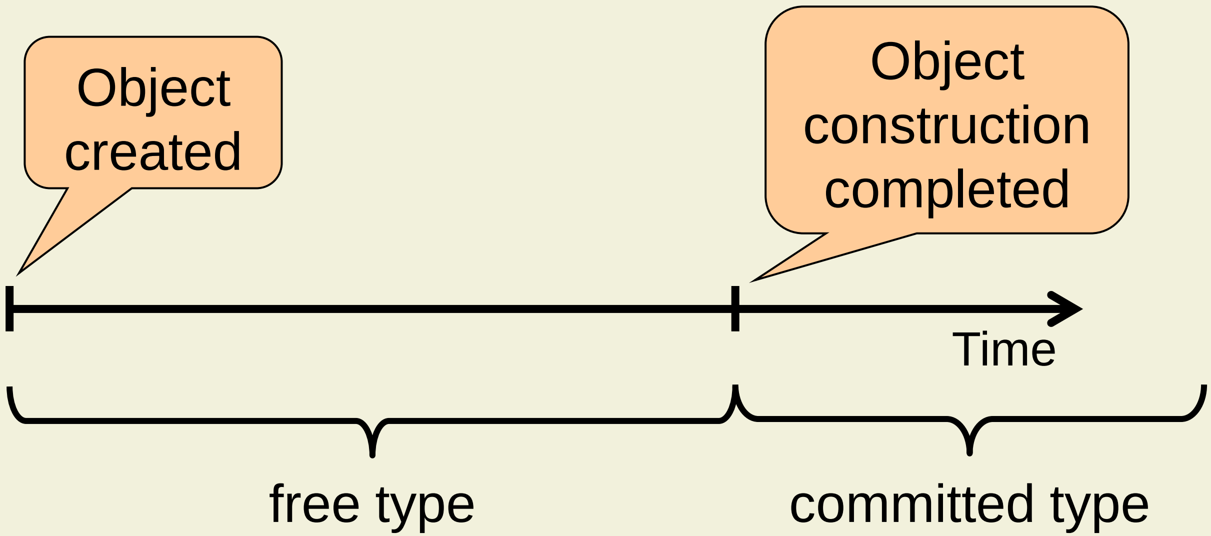
```
class Node {
  Node! next;   // cyclic list
  String! id;

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

  String! free getId( String! n )
  { return …; }
```

Call is permitted

this is of a free type

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?
- 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?
- Not if constructor initializes fields with free references

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

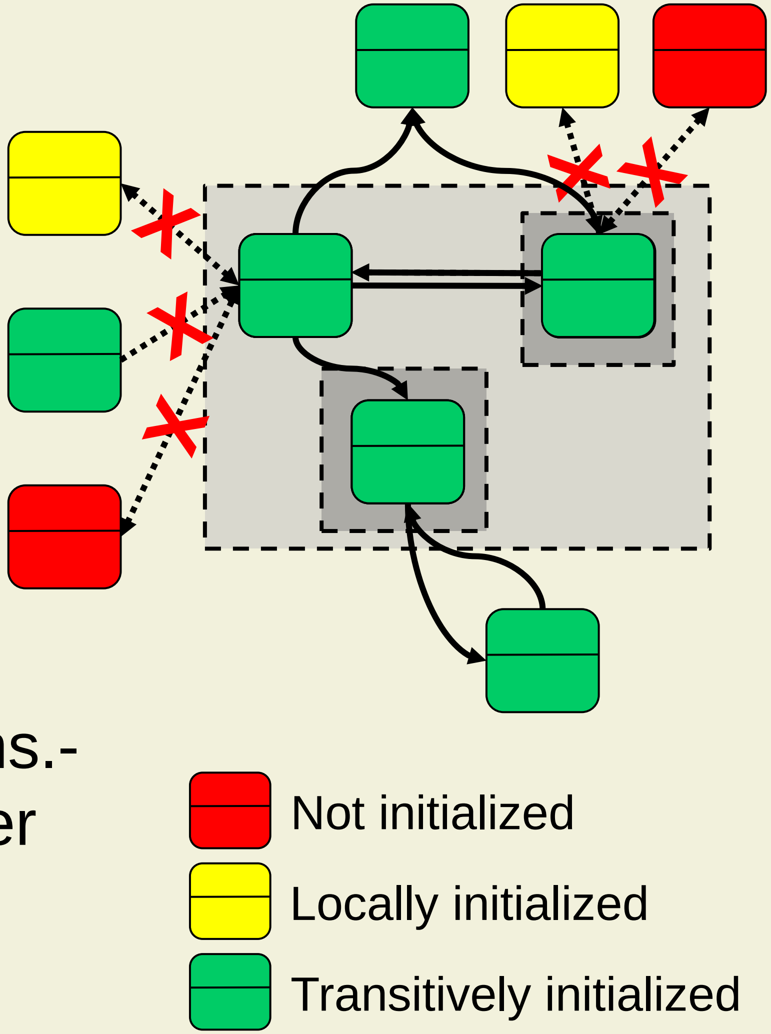
c is locally, but not transitively initialized

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

NullPointer Exception

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
  - All new objects are transitively initialized



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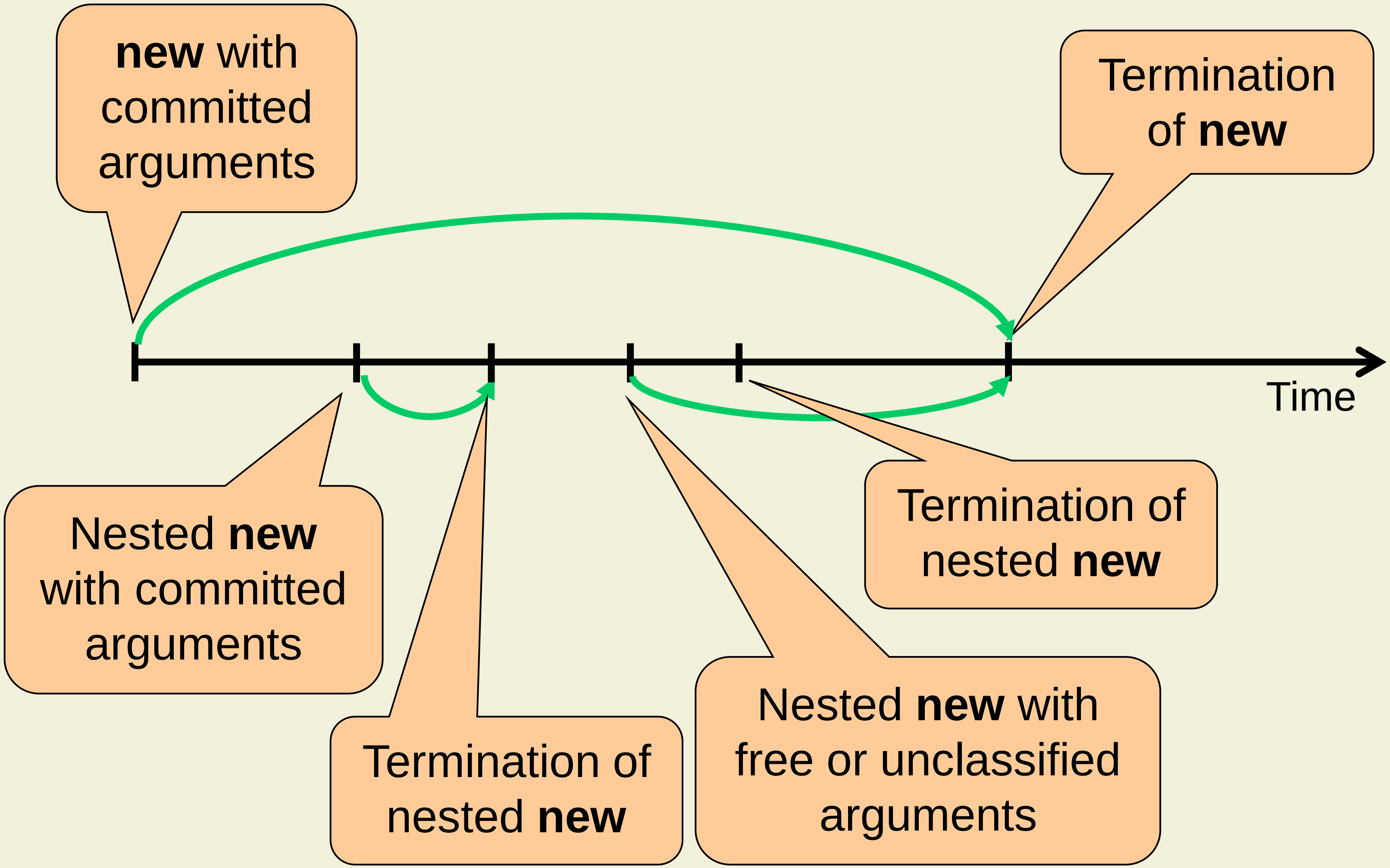
Completing Object Construction



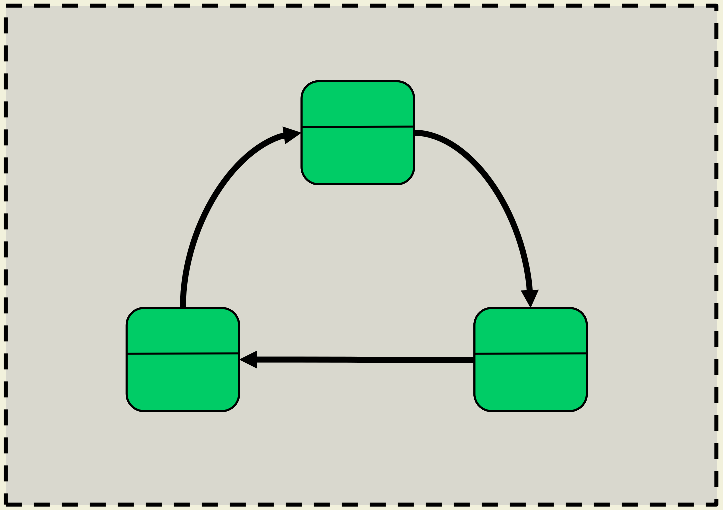
Type Rules: new-Expressions

- 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

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

Cyclic Structures: Example

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



```
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 );
  }
}
```

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

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.regis
  }

  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

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

  void run( ) {
    while( true ) {
      if( sensorValueChanged( ) )
        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;
  }
}
```

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;
  }
}
```

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 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

Possibly-null array with possibly-null elements

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";
   }
  }
}
```

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” };
```

- 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#

Changes type from free to committed

Summary

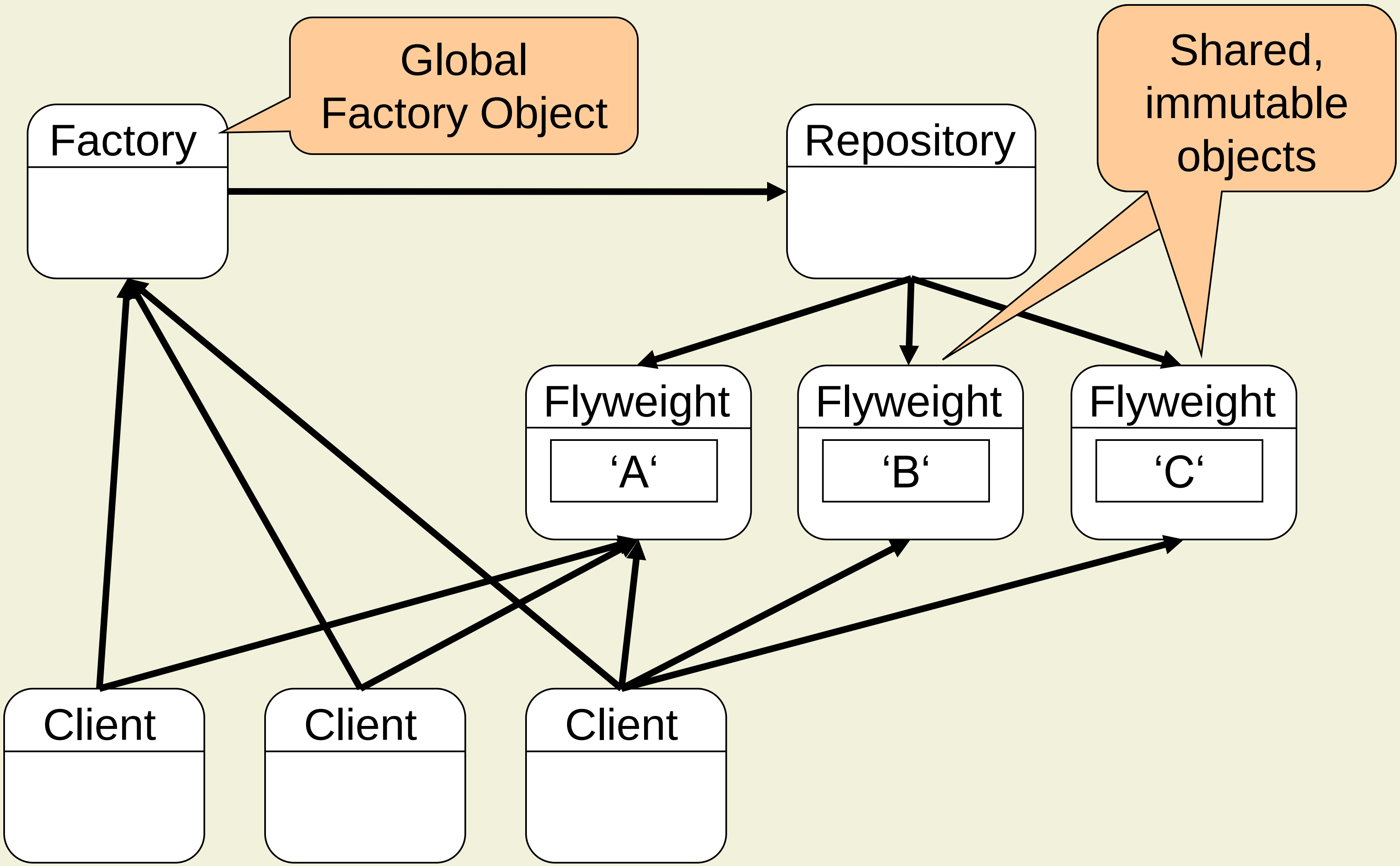
- Object initialization has to establish invariants
  - Non-nullness of fields is just an example

- 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

The Flyweight Pattern



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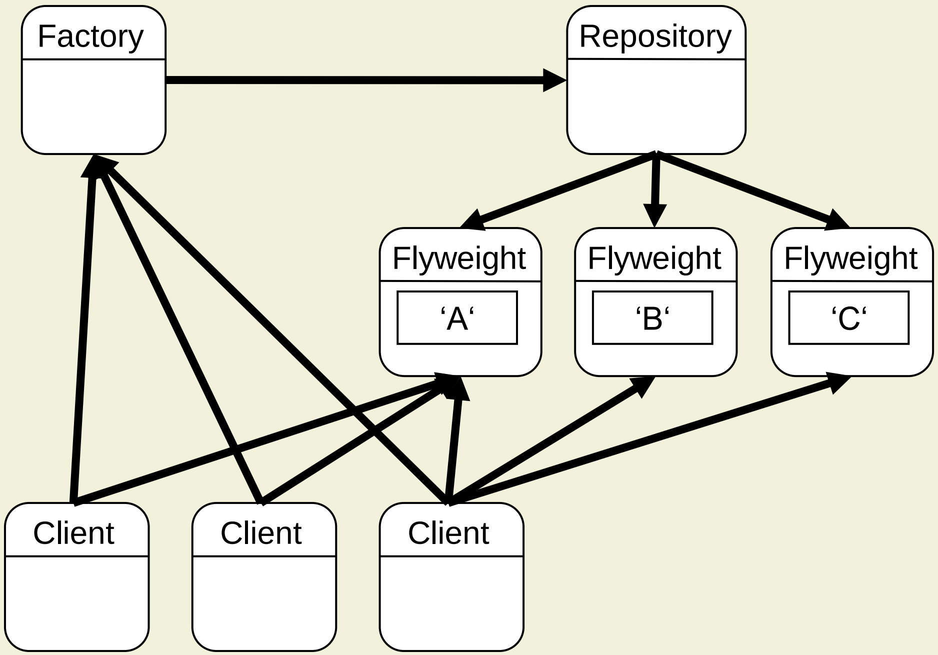
Global Data

- 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

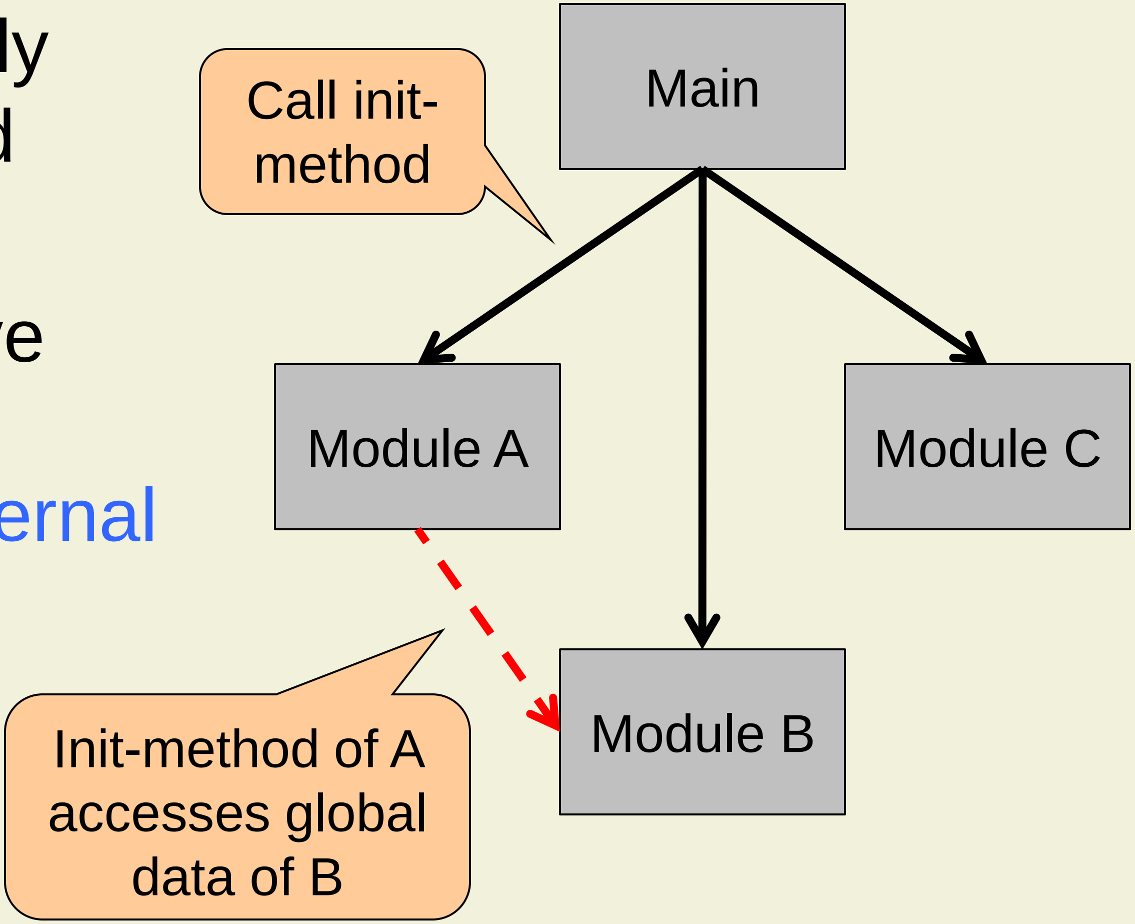
- Global variables store references to global data
- Initialization is done by explicit calls to init-methods

```
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: 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 C

  and 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

Initialization triggered here

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

Initialize UniqueID

Initialization already in progress

NullPointerException

Initialize Debug

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

Java

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