Concepts of Object-Oriented Programming

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Chair of Programming Methodology

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Visible States

- Invariants have to hold in pre- and poststates of methods executions but may be violated temporarily in between
- Pre- and poststates are called "visible states"

```
class Redundant {
  private int a, b;
  // invariant a == b

  public void set( int v ) {
    // invariant  of this holds
    a = v;
    // invariant of this violated
    b = v;
    // invariant  of this holds
  }
}
```

9. Object Invariants

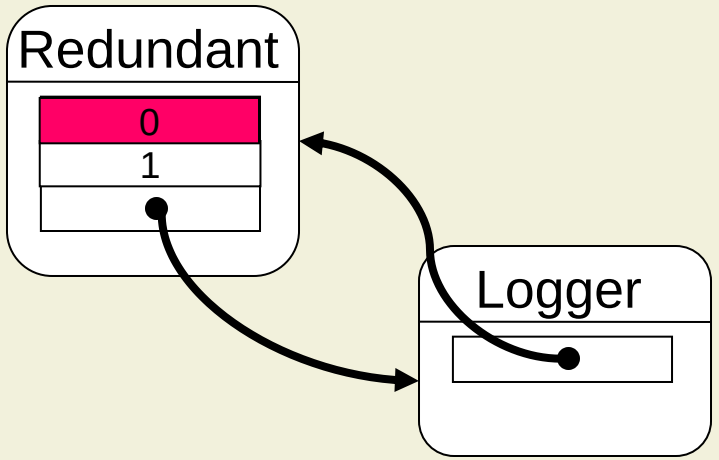
Call-backs

```
class Redundant {
  private int a, b;
  private Logger l;
  // invariant a == b
  public void set( int v ) {
    a = v;
    l.log( “Inside set” );
    b = v;
  }

  public int div( int v ) {
    return v / ( a – b + 1 );
  }
}
```

```
class Logger {
  private Redundant r;

  public void log( String m ) {
    System.out.println( m + r.div( 5 ) );
  }
}
```



Common Variations

- Self-calls

```
class Redundant {
  private int a, b;

  // invariant a == b

  public void set( int v ) {
    a = v; this.div( 5 ); b = v;
  }

  public int div( int v ) {
    return v / ( a – b + 1 );
  }
}
```

- Re-entrant monitors

```
class Redundant {
  private int a, b;

  // monitor invariant a == b

  public synchronized void set( int v ) {
    a = v; this.div( 5 ); b = v;
  }

  public synchronized int div( int v ) {
    return v / ( a – b + 1 );
  }
}
```

Java

Running Example

```
class Account {
  int balance;
  Currency! cur;
  Regulator! regulator;

  // invariant  cur == Currency.CHF ==> balance % 5 == 0;

  void Exchange( Currency! c ) {
    balance = cur.Convert( balance, c );
    cur = c;
    regulator.Report( this );
    if( cur == Currency.CHF )
      balance = balance / 5 * 5;
  }
  …
}
```

Solution 1: Re-establishing Invariants

- Check invariant before every method call
- Overly restrictive: most methods do not call back
- Too expensive for run-time checking

```
class Account {
  int balance;
  Currency! cur;
  Regulator! regulator;

  // invariant  cur == Currency.CHF
  //                    ==> balance % 5 == 0;

  void Exchange( Currency! c ) {
    balance = cur.Convert( balance, c );
    cur = c;
    if( cur.Equals( Currency.CHF ) )
      balance = Round( balance );
    regulator.Report( this );
  }
  … }
```

Solution 2: Call-back Analysis

- Statically analyze code of callee to detect call-backs
  - Check invariant before call only if call-back is possible
- Not modular
  - For dynamically-bound methods, all overrides need to be known

```
class Account {
  int balance;
  Currency! cur;
  Regulator! regulator;

  // invariant  cur == Currency.CHF
  //                    ==> balance % 5 == 0;

  void Exchange( Currency! c ) {
    balance = cur.Convert( balance, c );
    cur = c;
    regulator.Report( this );
    if( cur == Currency.CHF )
      balance = balance / 5 * 5;
  }
  … }
```

What if Regulator is an interface?

Solution 3: Explicit Requirements

- Specify in each precondition which invariants the method actually requires
- Check required invariants before method call

```
class Account {
  …
  // requires invariant of this and c;
  void Exchange( Currency! c ) {
    balance = cur.Convert( balance, c );
    cur = c;
    regulator.Report( this );
    if( cur == Currency.CHF )
      balance = balance / 5 * 5;
  }
  …
}
```

Explicit Requirements: Problems

- Writing the concrete invariant in precondition violates information hiding
- Some methods require a large number of invariants
  - For example, tree traversal

```
class Account {
  …
  // requires invariant of this and c;
  void Exchange( Currency! c ) {
    balance = cur.Convert( balance, c );
    cur = c;
    regulator.Report( this );
    if( cur == Currency.CHF )
      balance = balance / 5 * 5;
  }
  …
}
```

Solution 4: Dented Invariants

- Use boolean field to indicate whether object is valid or not
  - Can be used to turn invariant on and off
- Dented invariant holds in all visible states
- Explicit requirements can be stated using the valid-field

```
class Account {
  …
  boolean valid;

  // invariant  valid ==>
  //                  cur == Currency.CHF
  //                  ==> balance % 5 == 0;

  // requires this.valid && c.valid;
  void Exchange( Currency! c )
  { … }
  …
}
```

Re-establishing Dented Invariants

- Programmers might forget to set valid-field
- Invariants still need to be checked before method calls
- A method can break many invariants through direct field updates

```
class Account {
  boolean valid;

  void Exchange( Currency! c ) {
    balance = cur.Convert( balance, c );
    cur = c;
    regulator.Report( this );
    if( cur == Currency.CHF )
      balance = balance / 5 * 5;
  }
  …
}
```

valid not set to false

Dented invariant does not hold

Basic Spec# Methodology

- Each object has an implicit valid-field
  - Valid and mutable objects
- Each invariant is implicitly dented
- Object invariants can depend only on the fields of the **this** object (will be relaxed later)
- Enforce that dented invariants hold in all execution states, not just visible states
  - Un-dented invariant holds whenever an object is valid
- Valid objects must not be modified
  - Check for each field update o.f = e that o is mutable

Spec# Methodology: Example

```
class Account {
  …
  invariant cur == Currency.CHF ==> balance % 5 == 0;

  void Exchange( Currency! c )
    // requires this.valid && c.valid;
  {
    balance = cur.Convert( balance, c );
    cur = c;
    regulator.Report( this );
    if( cur == Currency.CHF )
      balance = balance / 5 * 5;
  }
  …
}
```

Invariant is implicitly dented

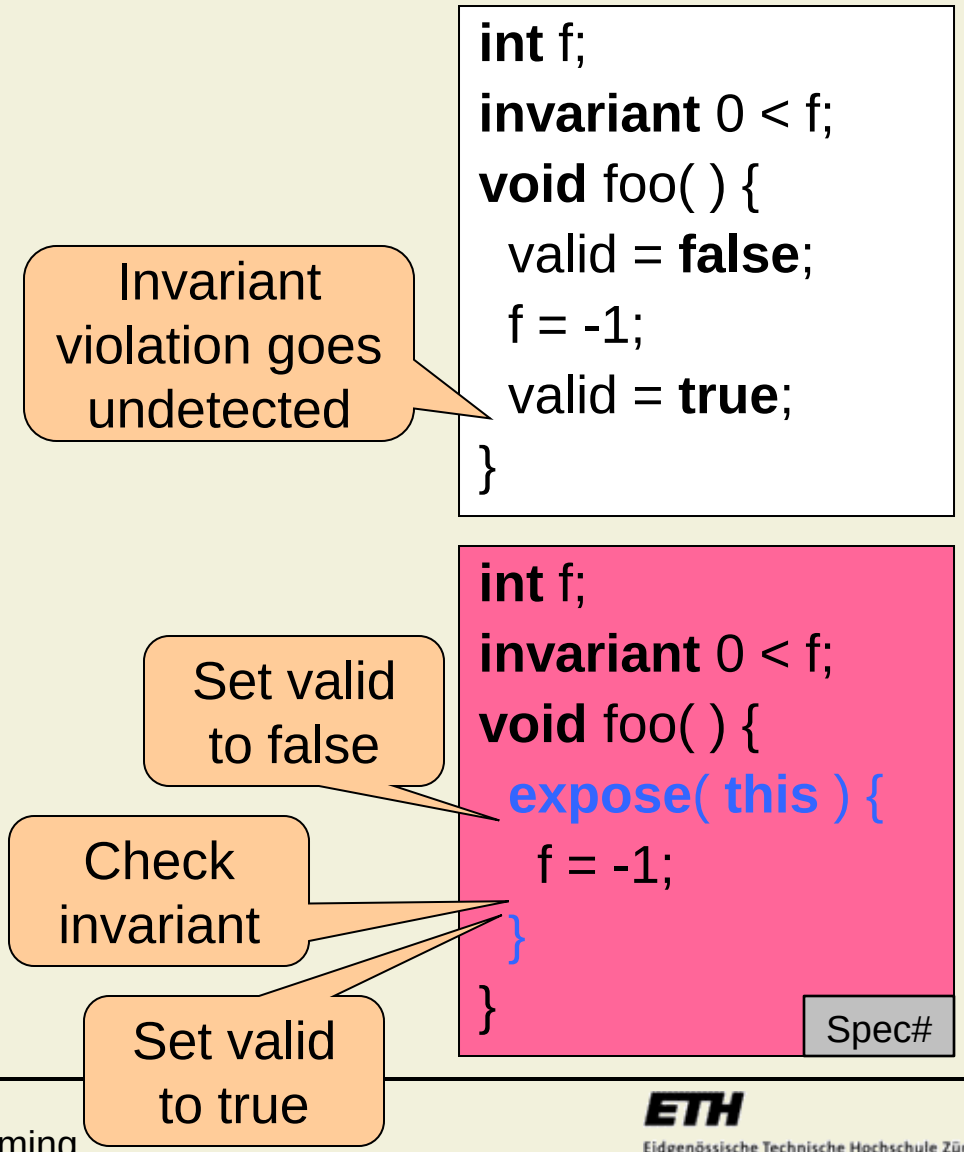
Check fails: receiver is not mutable

Implicit precondition: arguments are valid

Spec#

Maintaining Object Validity

- Setting the valid-field to true might break the dented invariant
- valid-field can be modified only through special **expose** block statement
  - Exposed object must be initially valid
  - Similar to non-reentrant lock-block



Example Revisited

```
class Account {
  invariant cur == Currency.CHF ==> balance % 5 == 0;

  void Exchange( Currency! c )
    // requires this.valid && c.valid;
  {
    expose( this ) {
      balance = cur.Convert( balance, c );
      cur = c;
      regulator.Report( this );
      if( cur == Currency.CHF )
        balance = balance / 5 * 5;
    }
  }
  … }
```

Check succeeds: **this** is valid

Check succeeds: receiver is mutable

Check succeeds: invariant holds

Spec#

Establishing Object Validity

- New objects are initially mutable
  - valid-Field is initialized to false
- After initialization, un-dented invariant is checked and valid-field is set to true
  - We ignore inheritance here

```
class Account {
  …
  invariant cur == Currency.CHF
                ==> balance % 5 == 0;

  Account( Regulator! r ) {
    cur = Currency.CHF;
    regulator = r;
  }
  …
}
```

Invariant holds since balance == 0

Implicit: **this**.valid = **true**;

Spec#

Basic Spec# Methodology: Summary

- Admissible invariants
  - The invariant of an object o may depend on fields of o (and constants)
- Checks (proof obligations)
  - Invariant of o holds after o has been initialized
  - Invariant of o holds at the end of each **expose**(o) block
  - Every expose operation is done on a valid object
  - Every field update is done on a mutable receiver
- Recall: we ignore inheritance here

Call-backs in Spec#: Example

```
class Account {
  void Exchange( Currency! c )
    // requires this.valid && c.valid;
  {
    expose( this ) {
      …
      regulator.Report( this );
      …
    }
  }
  int GetBalance( )
    // requires this.valid
  { return balance; }
}
```

Spec#

In principle, methods can be called while invariant is broken

This call is forbidden since precondition does not hold

Requirement about expected invariants

```
class Regulator {
  void Report( Account! a
    // requires this.valid && a.valid;
  {
    int b = a.GetBalance( );
    // …
  }
  …
}
```

Spec#

Call-backs in Spec#: Example (cont'd)

```
class Account {
  void Exchange( Currency! c )
    // requires this.valid && c.valid;
  {
    expose( this ) {
      …
      regulator.Report( this );
      …
    }
  }
  int GetBalance( )
    // requires this.valid
  { return balance; }
}
```

Spec#

Call is allowed since precondition holds

```
class Regulator {
  void Report( Account! a )
    // requires this.valid;
  {
    int b = a.GetBalance( );
    // …
  }
  …
}
```

Spec#

a's invariant is not expected

Call-back is forbidden since precondition does not hold

Call-backs in Spec#: Example (cont'd)

```
class Account {
  void Exchange( Currency! c )
    // requires this.valid && c.valid;
  {
    expose( this ) {
      …
      regulator.Report( this );
      …
    }
  }
  int GetBalance( )
    // requires true;
  { return balance; }
}
```

Spec#

Call is allowed since precondition holds

No invariant expected

```
class Regulator {
  void Report( Account! a )
    // requires this.valid;
  {
    int b = a.GetBalance( );
    // …
  }
  …
}
```

Spec#

a's invariant not expected

Call-back is allowed since precondition holds

9. Object Invariants

9.1 Call-backs

9.2 Invariants of Object Structures

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Multi-Object Invariants: Example

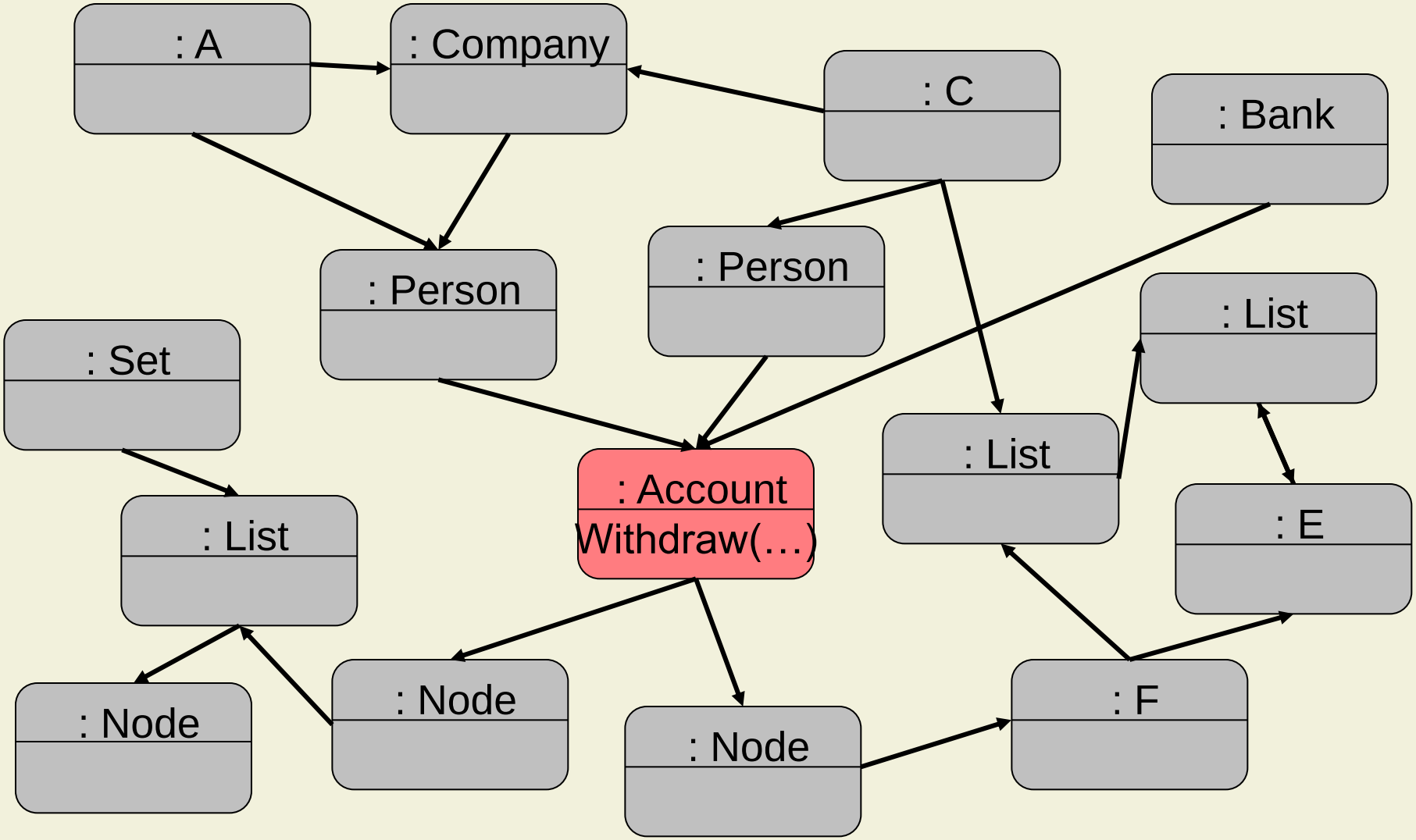
```
class Account {
  …

  void Withdraw( int amount )
    requires cur == Currency.CHF
                 ==> amount % 5 == 0;
    ensures balance ==
                 old( balance ) – amount;
  {
    expose( this ) {
      balance = balance – amount;
    }
  }
}
```

Field update might break invariants of client objects

```
class Person {
  Account! savings;

  invariant 0 <= savings.balance;
  …
}
```

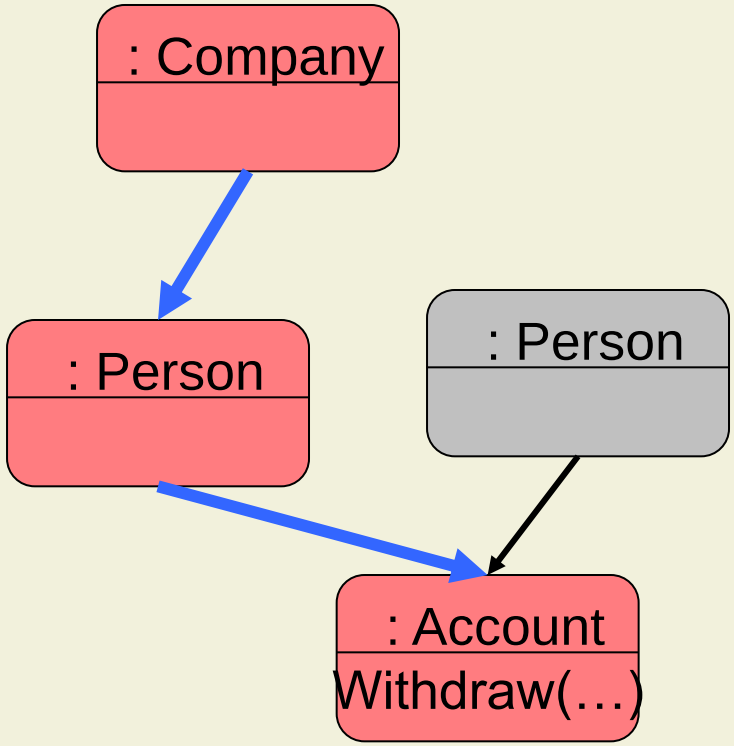
Invariant depends on field of another object

Finding Dependent Objects



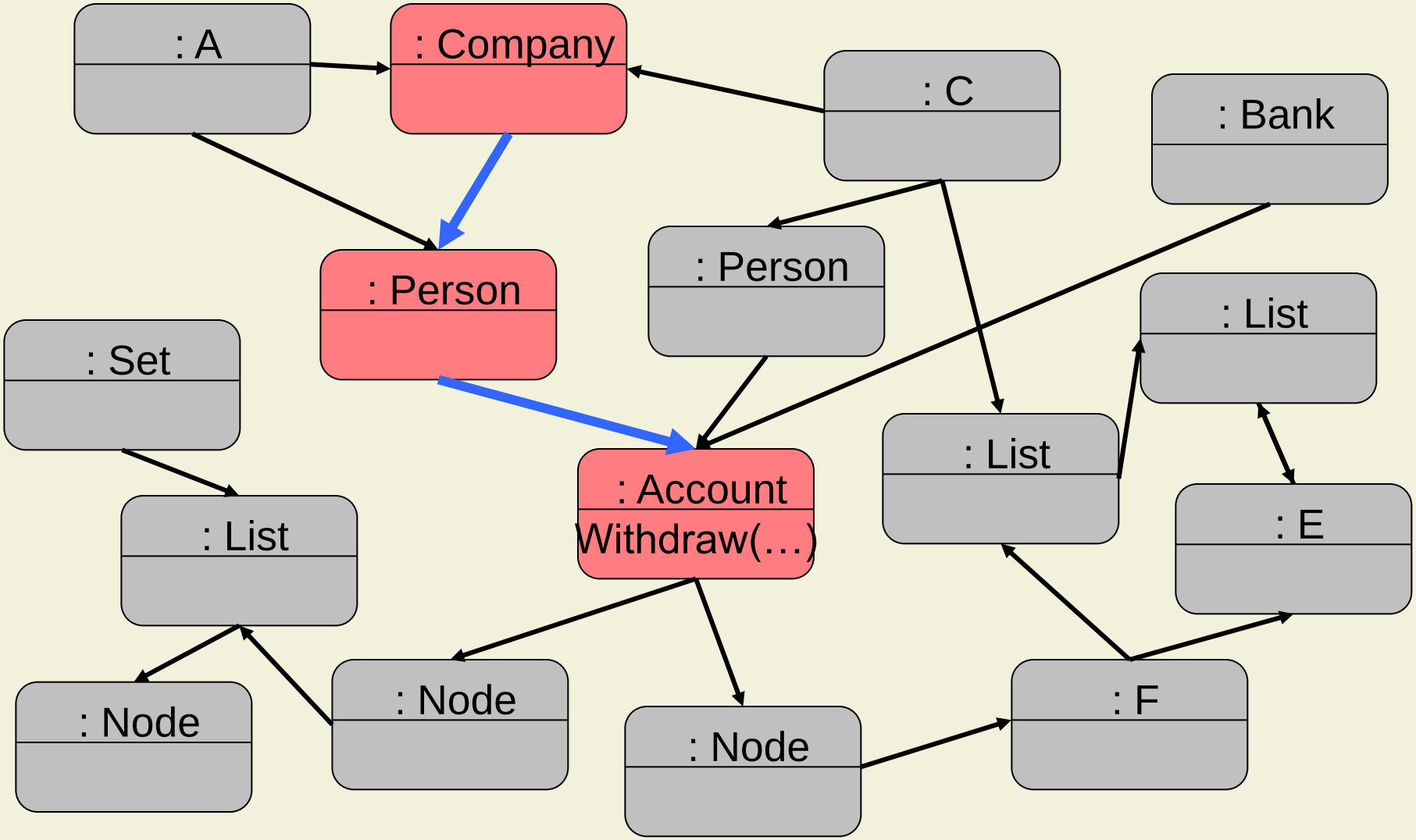
Ownership-Based Invariants

- Admissible invariants
  - The invariant of an object o may depend on fields of o and objects (transitively) owned by o (and constants)



- Requirement: when an object o is mutable, so are o's (transitive) owners
  - Because an update of o might break the owners' invariants

Using Ownership to Limit Dependencies



Admissible Ownership-Based Invariants

```
class Person {
  Account! savings;
  invariant 0 <= savings.balance;
  …
}
```

Not admissible: invariant depends on field of another object that is not owned by **this**

Use topological type system

Spec# syntax: [Rep]

```
class Person {
  rep Account! savings;
  invariant 0 <= savings.balance;
  …
}
```

Admissible: savings is owned by **this**

Mutable Owners: Example

```
class Account {
  …

  void Withdraw( int amount )
    requires cur == Currency.CHF
                 ==> amount % 5 == 0;
    ensures balance ==
                 old( balance ) – amount;
  {
    expose( this ) {
      balance = balance – amount;
    }
  }
}
```

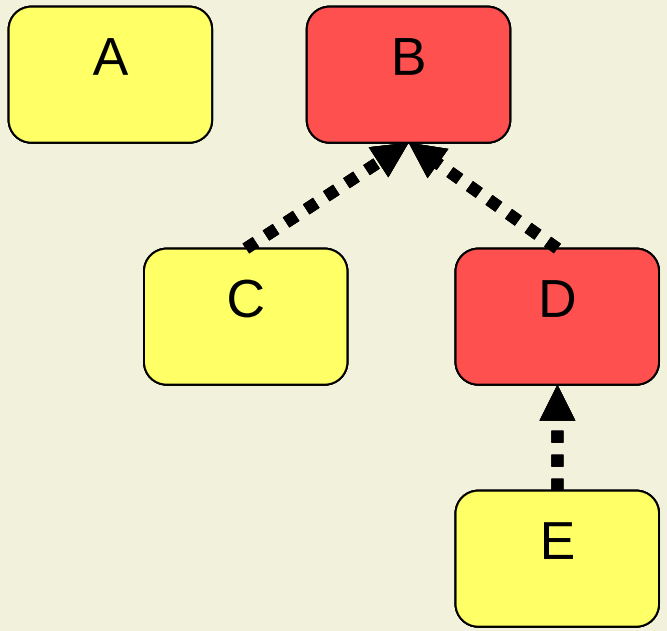
```
class Person {
  rep Account! savings;

  invariant 0 <= savings.balance;

  void Donate( )
  {
    savings.Withdraw( 1000 );
  }
}
```

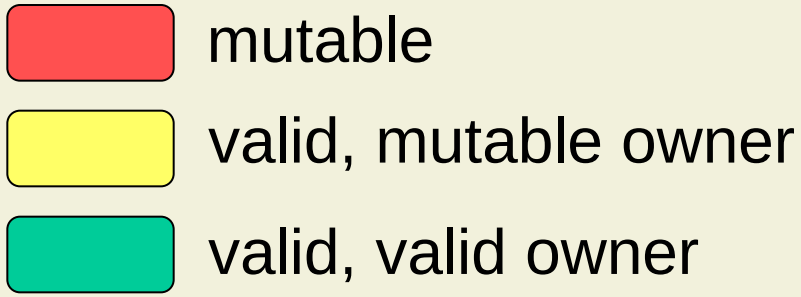
This call might break the invariant of **this**

Invariant of **this** is not checked!

Enforcing Mutable Owners

- Rules
  - Expose owner before owned object
  - Un-expose in reverse order
- Additional checks for **expose**(o)
  - Before expose, o must be valid and o's owner must be mutable
  - At the end of expose, all objects owned by o must be valid





Mutable Owners: Example (cont'd)

```
class Account {
  …

  void Withdraw( int amount )
    // requires valid && !owner.valid
    requires cur == Currency.CHF
                 ==> amount % 5 == 0;
    ensures balance ==
                 old( balance ) – amount;
  {
    expose( this ) {
      balance = balance – amount;
    }
  }
}
```

```
class Person {
  rep Account! savings;

  invariant 0 <= savings.balance;

  void Donate( )
    // requires valid && !owner.valid
  {
    savings.Withdraw( 1000 );
  }
}
```

This call is forbidden since precondition does not hold

Mutable Owners: Example (cont'd)

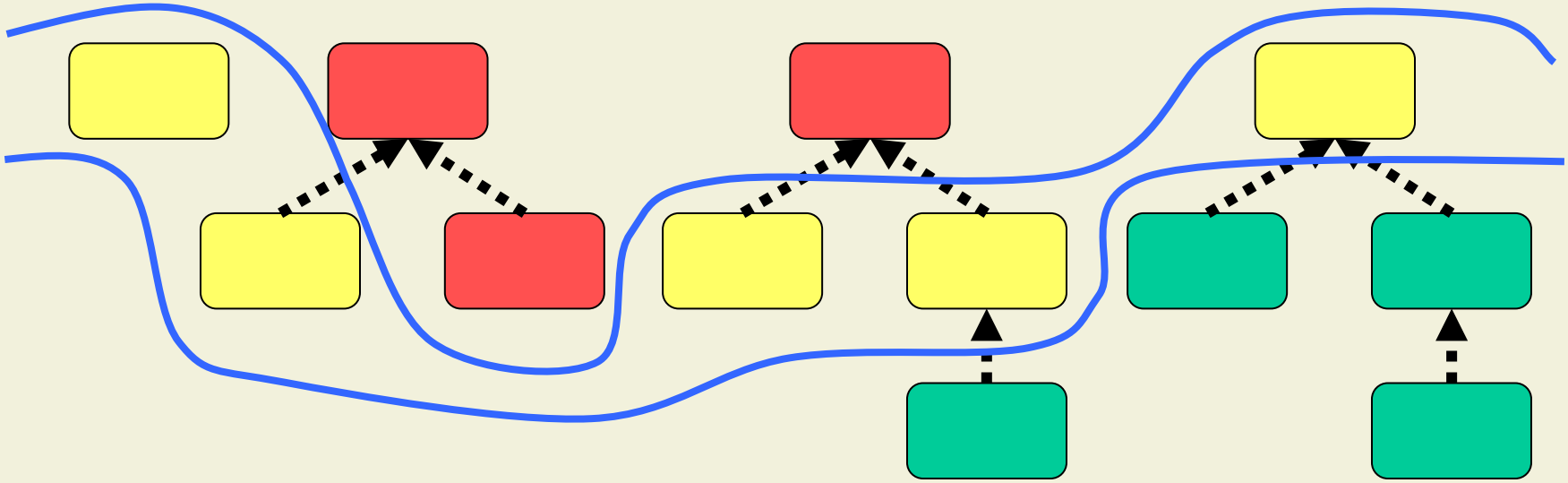
```
class Account {
  …

  void Withdraw( int amount )
    // requires valid && !owner.valid
    requires cur == Currency.CHF
                 ==> amount % 5 == 0;
    ensures balance ==
                 old( balance ) – amount;
  {
    expose( this ) {
      balance = balance – amount;
    }
  }
}
```

```
class Person {
  rep Account! savings;

  invariant 0 <= savings.balance;

  void Donate( )
    // requires valid && !owner.valid
  {
    expose( this ) {
      savings.Withdraw( 1000 );
    }
  }
}
```

Call is allowed since precondition holds

Invariant check fails (add precondition to fix)

Heap Snapshot



mutable

valid, mutable owner

valid, valid owner

Spec# Methodology: Summary

- Admissible invariants
  - The invariant of an object o may depend on fields of o and objects (transitively) owned by o (and constants)
- Checks (proof obligations)
  - Owner of newly created object is mutable
  - Invariant of o holds after o has been initialized
  - Invariant of o holds at the end of each **expose**(o) block and all objects owned by o are valid
  - Every expose operation is done on a valid object with a mutable (or no) owner
  - Every field update is done on a mutable receiver

Spec# Methodology: Observations

- Methodology relies on encapsulation of object structures
  - No strict enforcement of owner-as-modifier discipline
  - But: owner must be exposed before owned object
- Responsibility for invariant checking is divided
  - A method implementation is responsible for the objects in the context of the receiver
  - A caller is responsible for the objects in its context
- Ownership-based invariants are too restrictive for many useful examples

Invariants and Immutability

- Immutable objects can be freely shared
- Invariants may depend on the state of shared immutable objects
- Immutability often leads to more reliable programs
  - Especially for concurrency
  - If performance permits

```
[Immutable] class Integer {
  int value;
  …
}
```
Spec#

```
class Client {
  Integer! i;
  invariant 0 < i.value;
  …
}
```
No ownership necessary

Spec#

Invariants and Monotonicity

- Many properties of objects evolve monotonically
  - Numbers grow or shrink monotonically
  - Reference go from null to non-null
- Invariants may depend on properties of shared objects guaranteed by their history constraint

```
class Counter {
  int value;
  // constraint old( value ) <= value;
  …
}
```

```
class Client {
  Counter! c;
  invariant 0 < c.value;
  …
}
```

No ownership necessary

Invariants and Visibility

- Invariants may depend on fields of shared objects if a modular static analysis can determine all necessary checks

- Invariant and field are declared in the same module
  - Common example: recursive data structures

```
class Person {
  Person spouse;
  invariant spouse == null ||
            spouse.spouse == this;
…
}
```

No ownership necessary

Spec#

Summary

- Sound, modular checking of object invariants is surprisingly difficult
  - Call-backs
  - Multi-object invariants
  - Inheritance

- Spec# is the first system to support sound, modular verification of object invariants
  - Efficient run-time checking does not seem feasible

- Spec# is open source: specsharp.codeplex.com