How banks can maintain stability

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Class-invariant based reasoning with semantic collaboration

Reasoning about OO

I'll present a framework for reasoning about the functional correctness of object-oriented programs based on class (object) invariants.

Reasoning about OO

Methodology: semantic collaboration

– includes an ownership scheme

Implementation: AutoProof verifier

– for simplicity, I will also use “AutoProof” to refer to the methodology

Reference language: Eiffel

– but practically everything applicable to Java/JML and similar OO languages

Main features of the framework

- Targets idiomatic OO structures (OO patterns)
- Flexible (semantic)
- Reasonably concise (defaults)
- Applicable to realistic implementations (data structure library)
- Sequential programs only

AutoProof in a nutshell

AutoProof is an auto-active verifier for Eiffel

- Prover for functional properties
- All-out support of object-oriented idiomatic structures (e.g. patterns)
  - Based on class invariants

Nadia Polikarpova

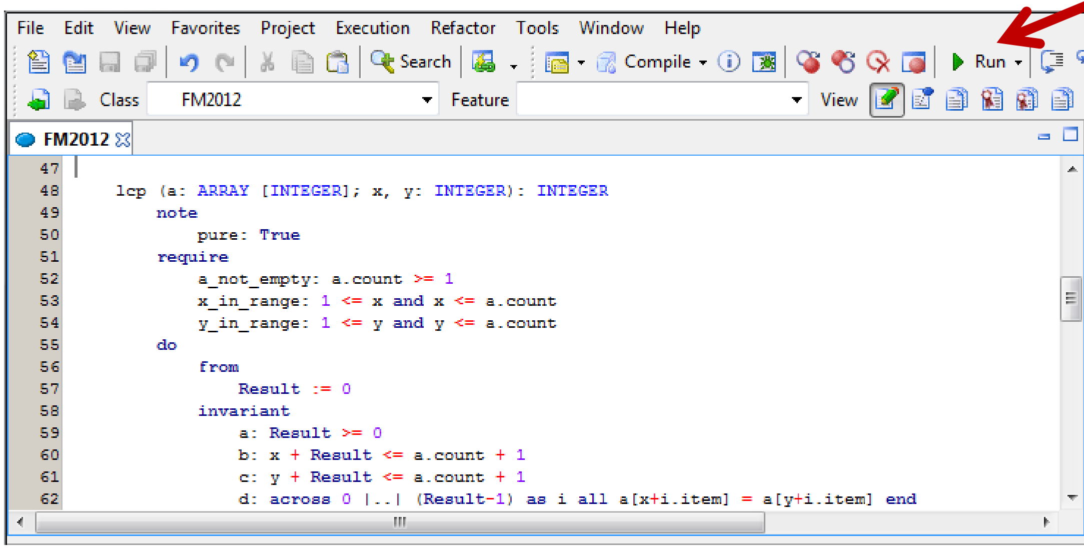
Julian Tschannen

Bertrand Meyer

Auto-active user/tool interaction

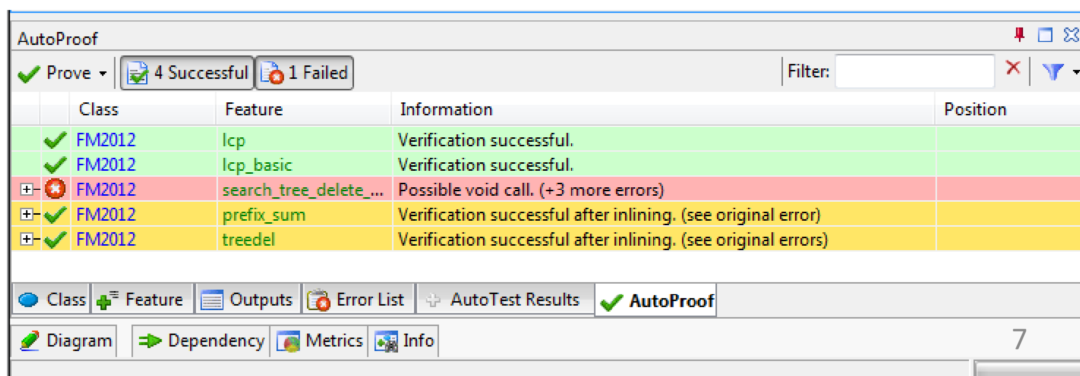
1. Code + Annotations

2. Push button

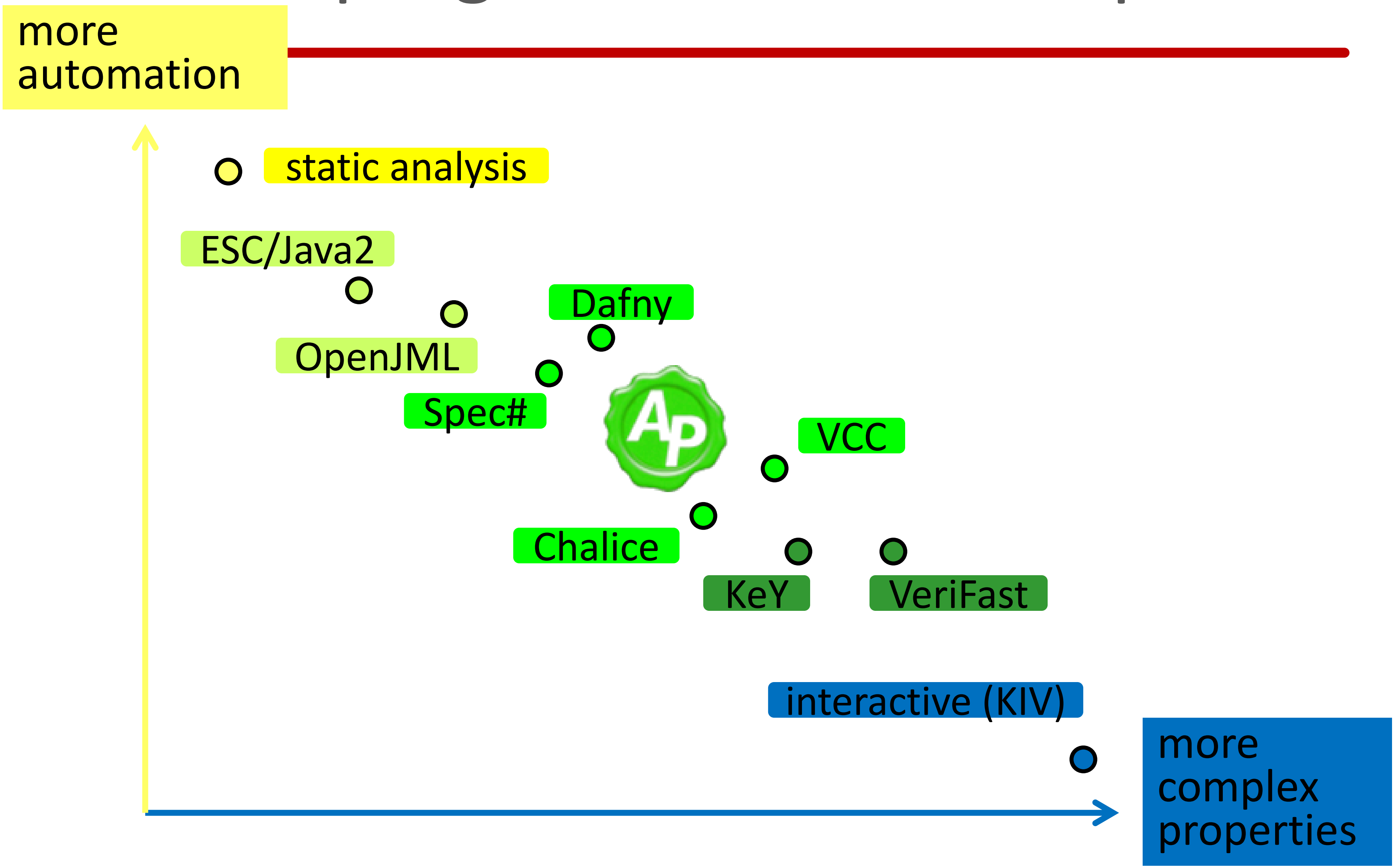


3. Verification outcome

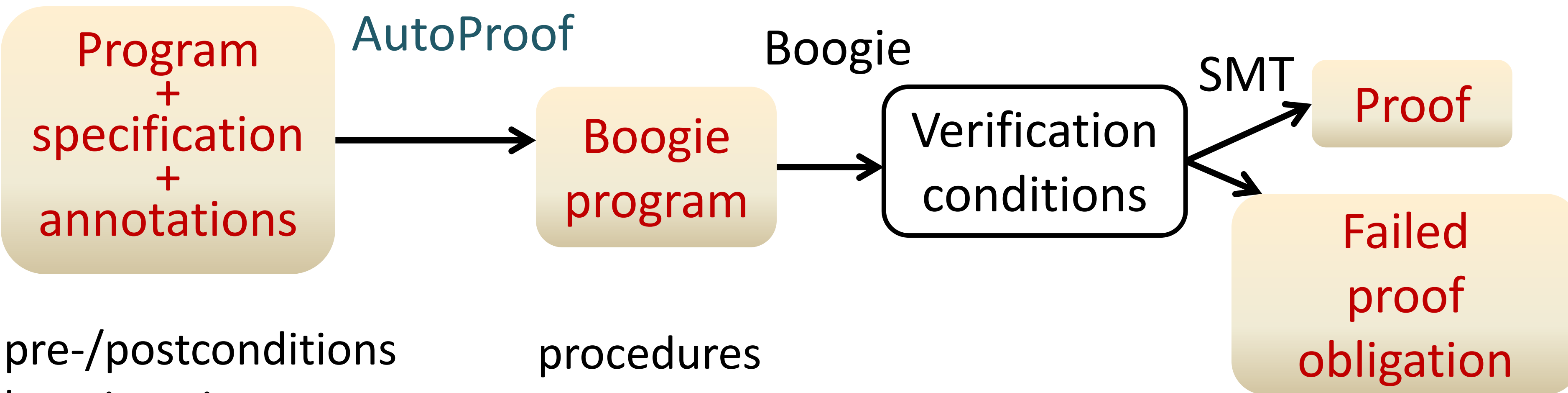
4. Correct/Revise



Sound program verifiers compared



How AutoProof works



pre-/postconditions
loop invariants
intermediate assertions
class invariants
frame specification
object dependencies

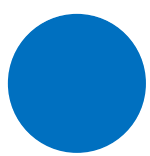
procedures
axioms
specification functions
memory model
background theory
triggers

Reasoning with class invariants

Class invariants are a natural way to reason about object-oriented programs:

invariant = consistency of objects

ACCOUNT



```
invariant
    balance >= 0
```

Demo: AutoProof warmup

AutoProof verifies a basic version of the bank ACCOUNT class

```
deposit (amount: INTEGER)

withdraw (amount: INTEGER)
```

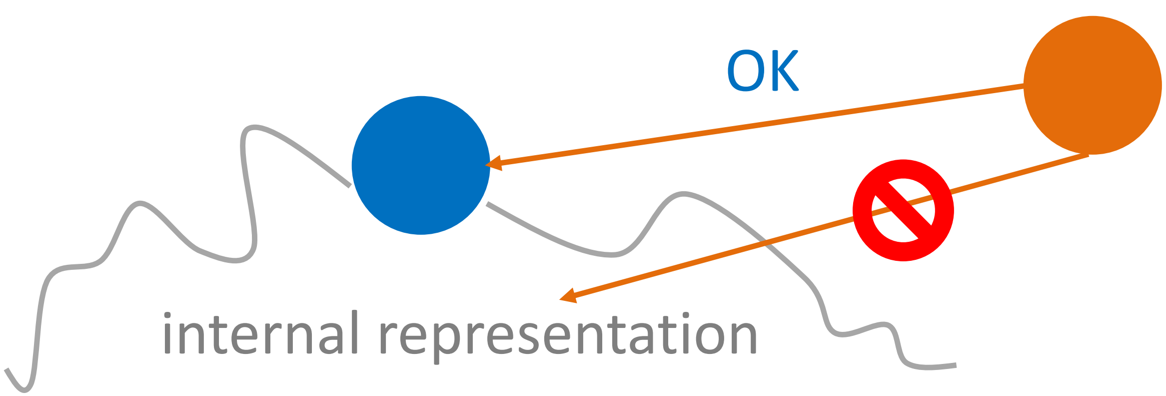
Follow this demo at:
http://comcom.csail.mit.edu/e4pubs/#demo-key
(Tab account_warmup.e)

Stability of invariant reasoning

Invariant-based reasoning should ensure stability:

stability = an operation can affect
an object's invariant only if
it modifies the object explicitly

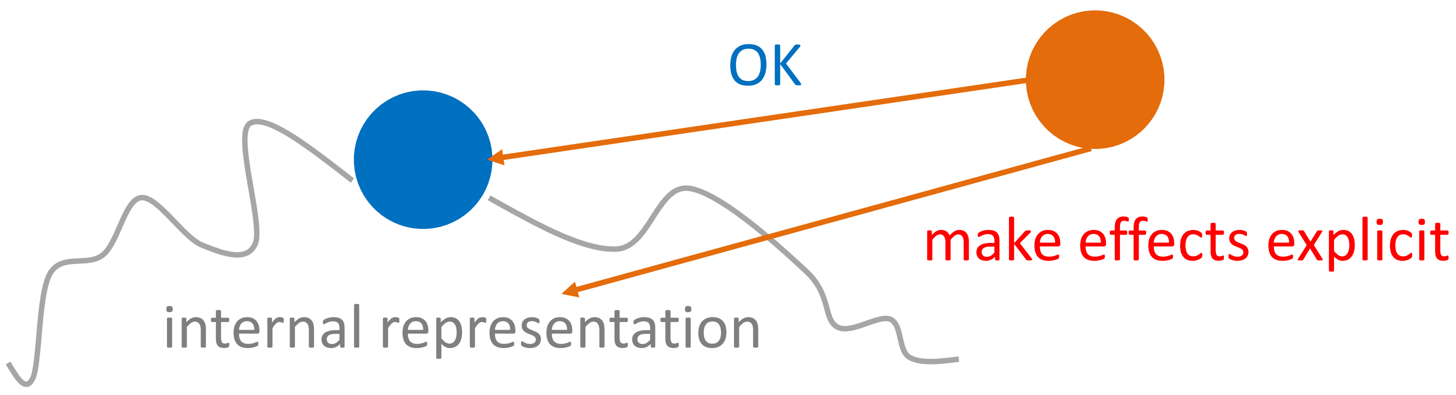
With stability, no one can invalidate an object behind its back!



Stability and encapsulation

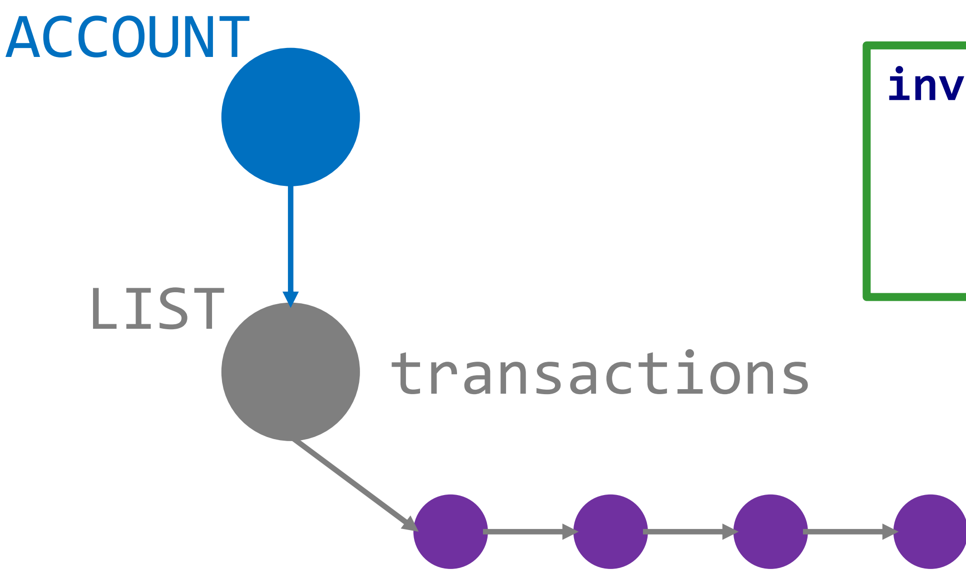
Invariant-based reasoning with stability:

- enforces encapsulation/information hiding
- simplifies client reasoning
- retains flexibility



Multi-object structures

Object-oriented programs involve multiple objects (duh!), whose consistency is often mutually dependent

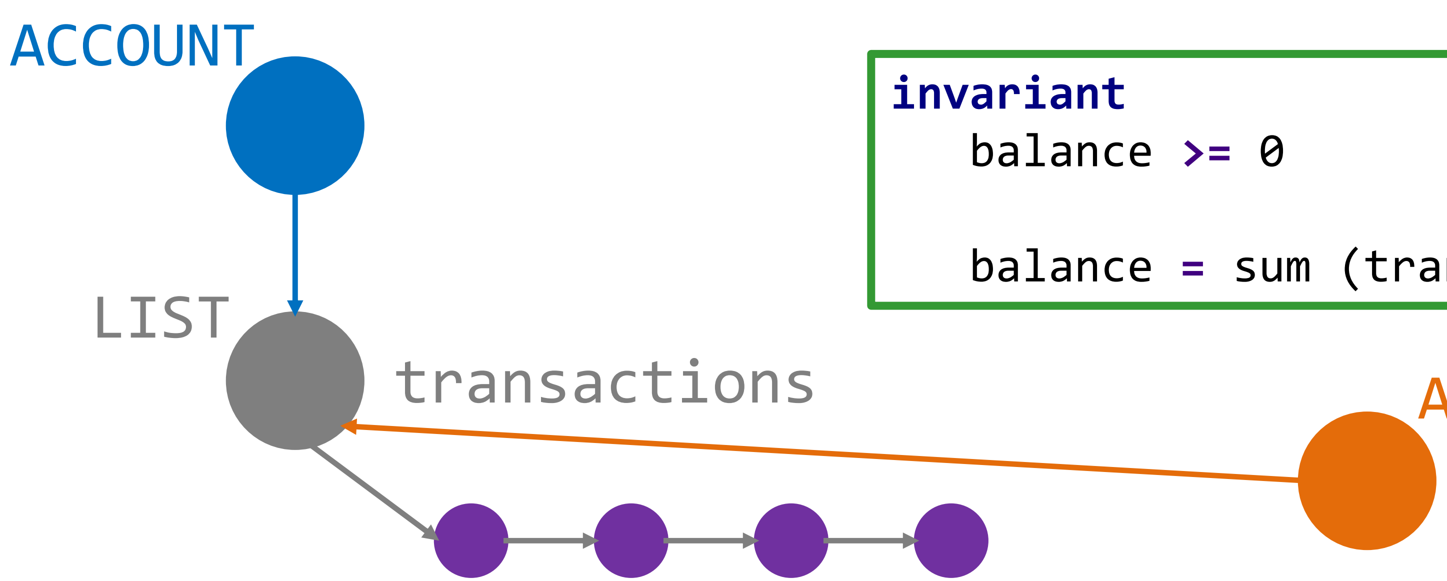



```
invariant
    balance >= 0

    balance = sum (transactions)
```

Consistency of multi-object structures

Mutually dependent object structures require extra care to enforce, and reason about, consistency (cmp. encapsulation)

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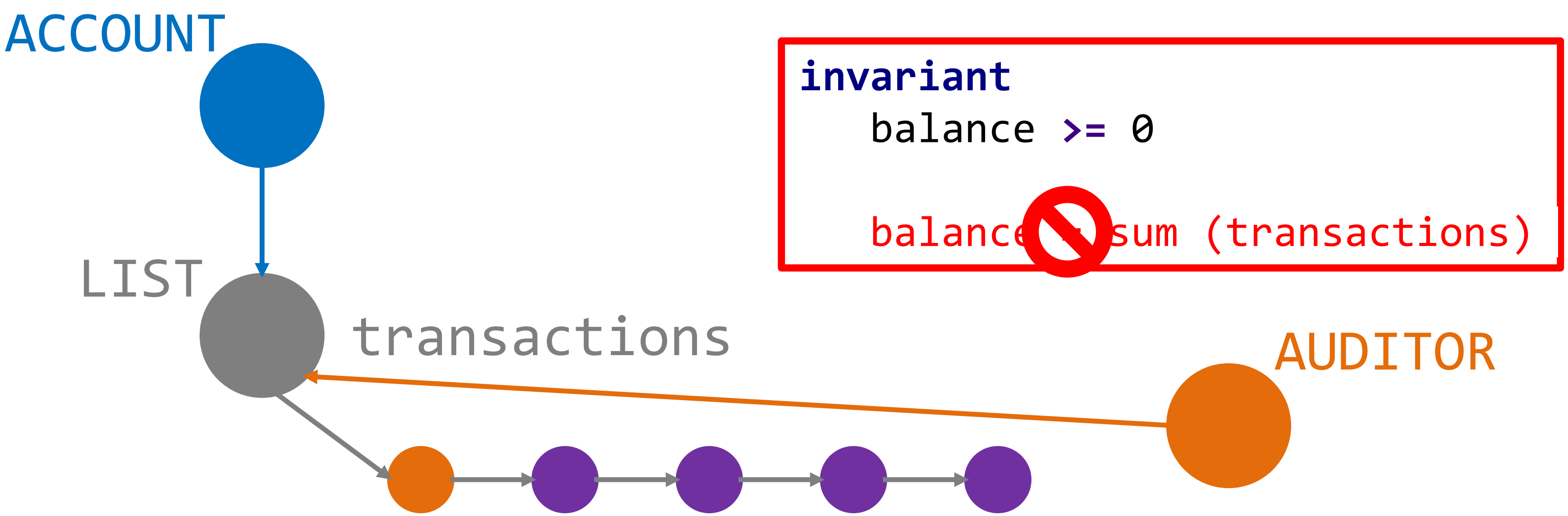


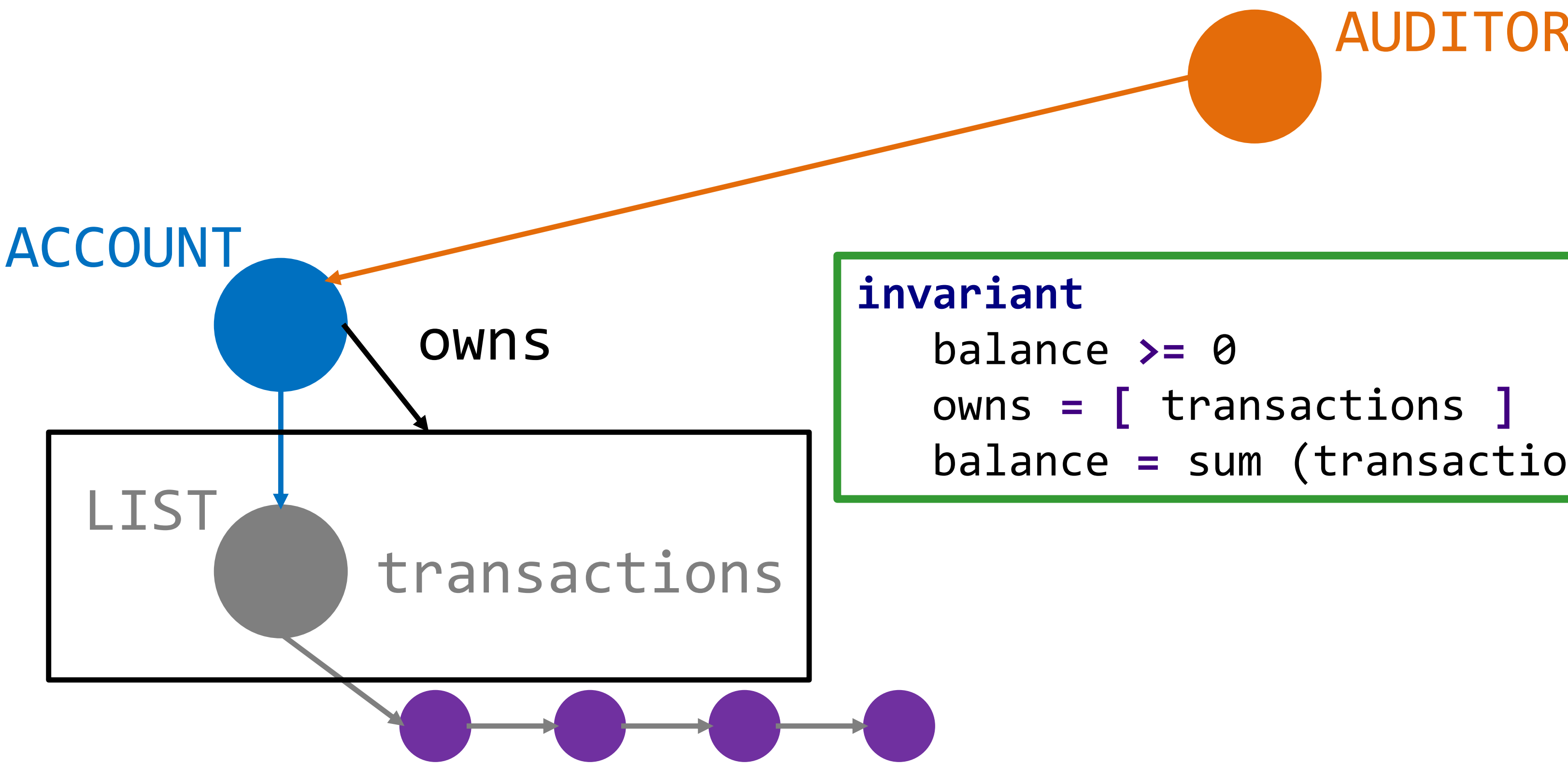
Open and closed objects

When (at which program points) must class invariants hold? To provide flexibility, objects in AutoProof can be open or closed

	CLOSED	OPEN
Object:	consistent	inconsistent
State:	stable	transient
Invariant:	holds	may not hold

Ownership

For hierarchical object structures, AutoProof offers an ownership protocol




```
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    balance = sum (transactions)
```

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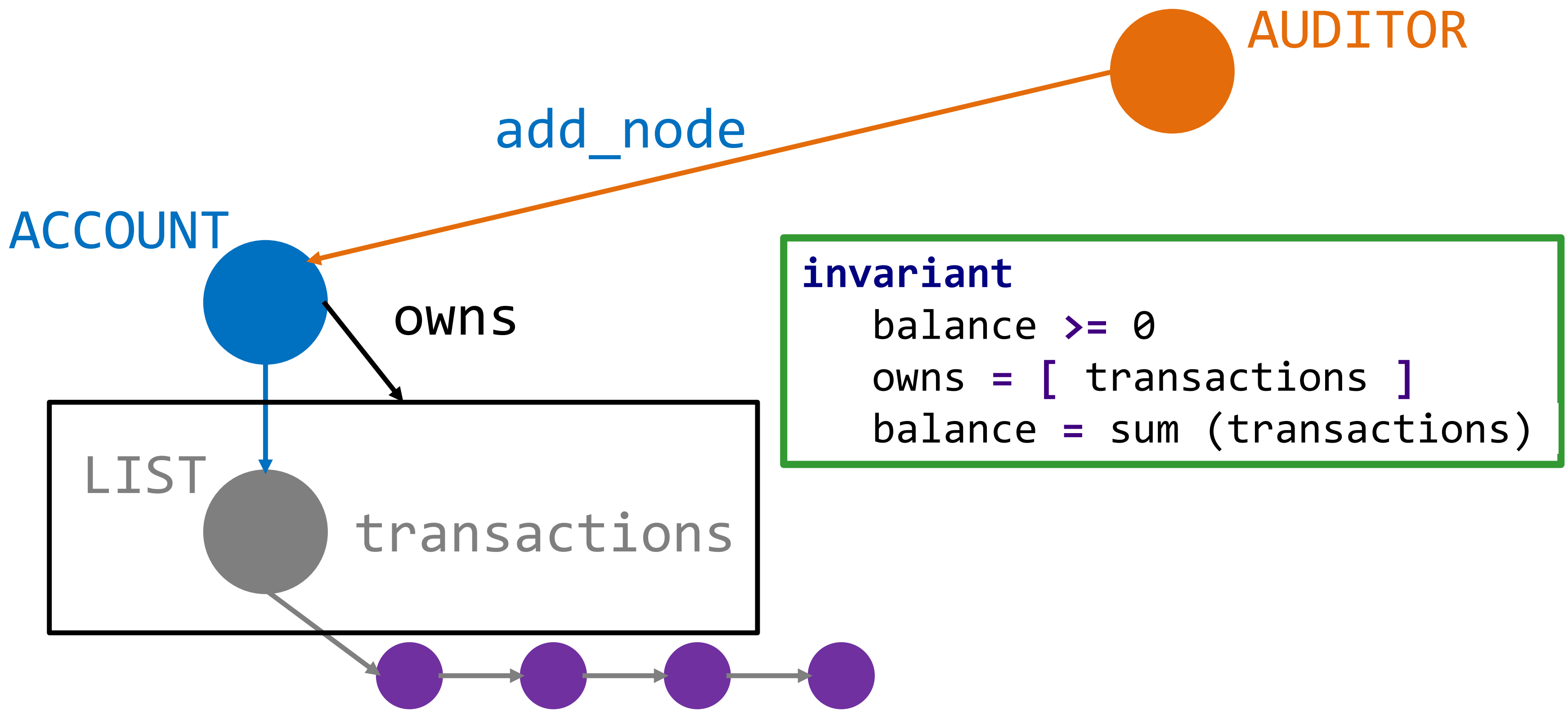

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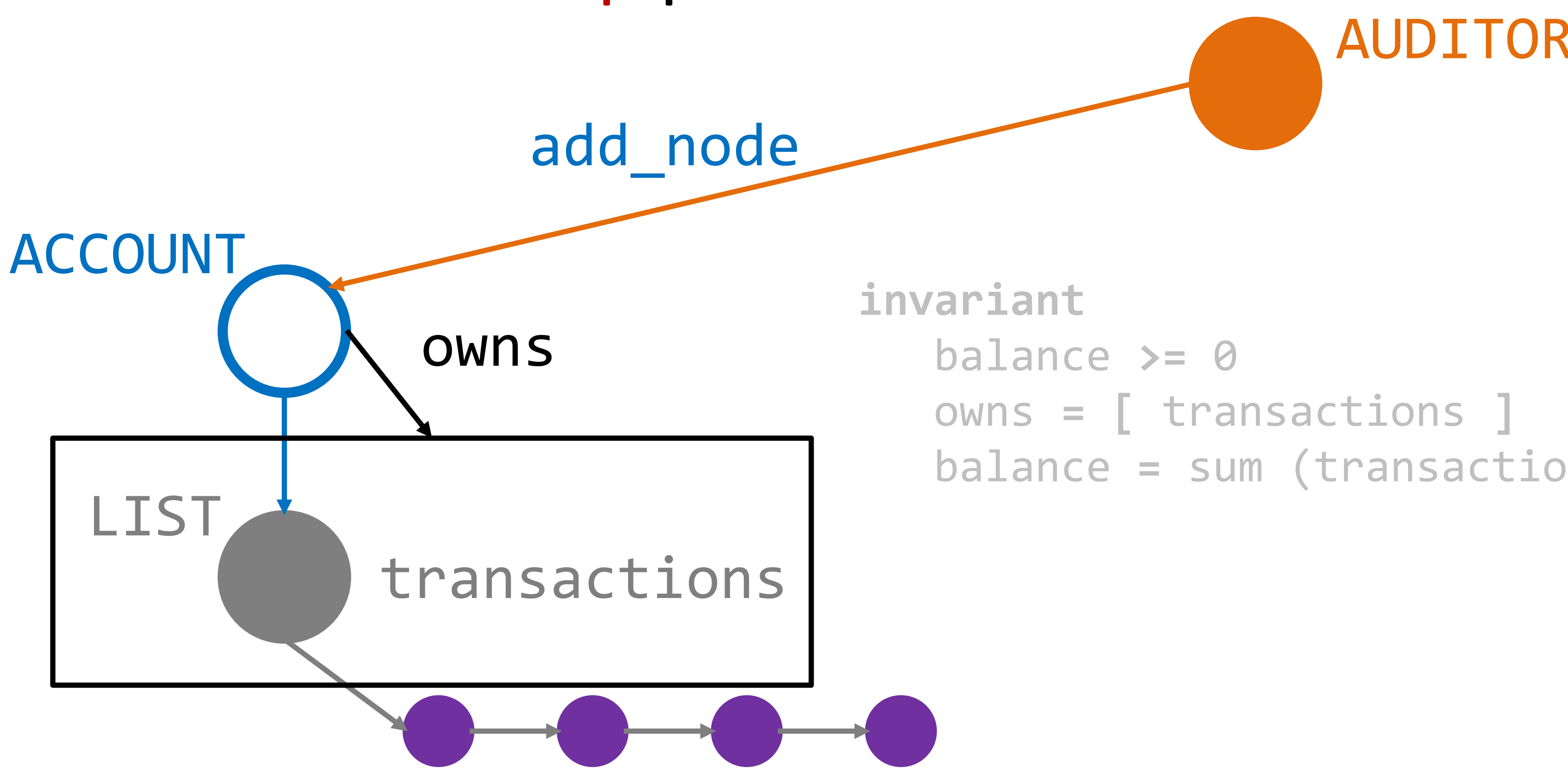


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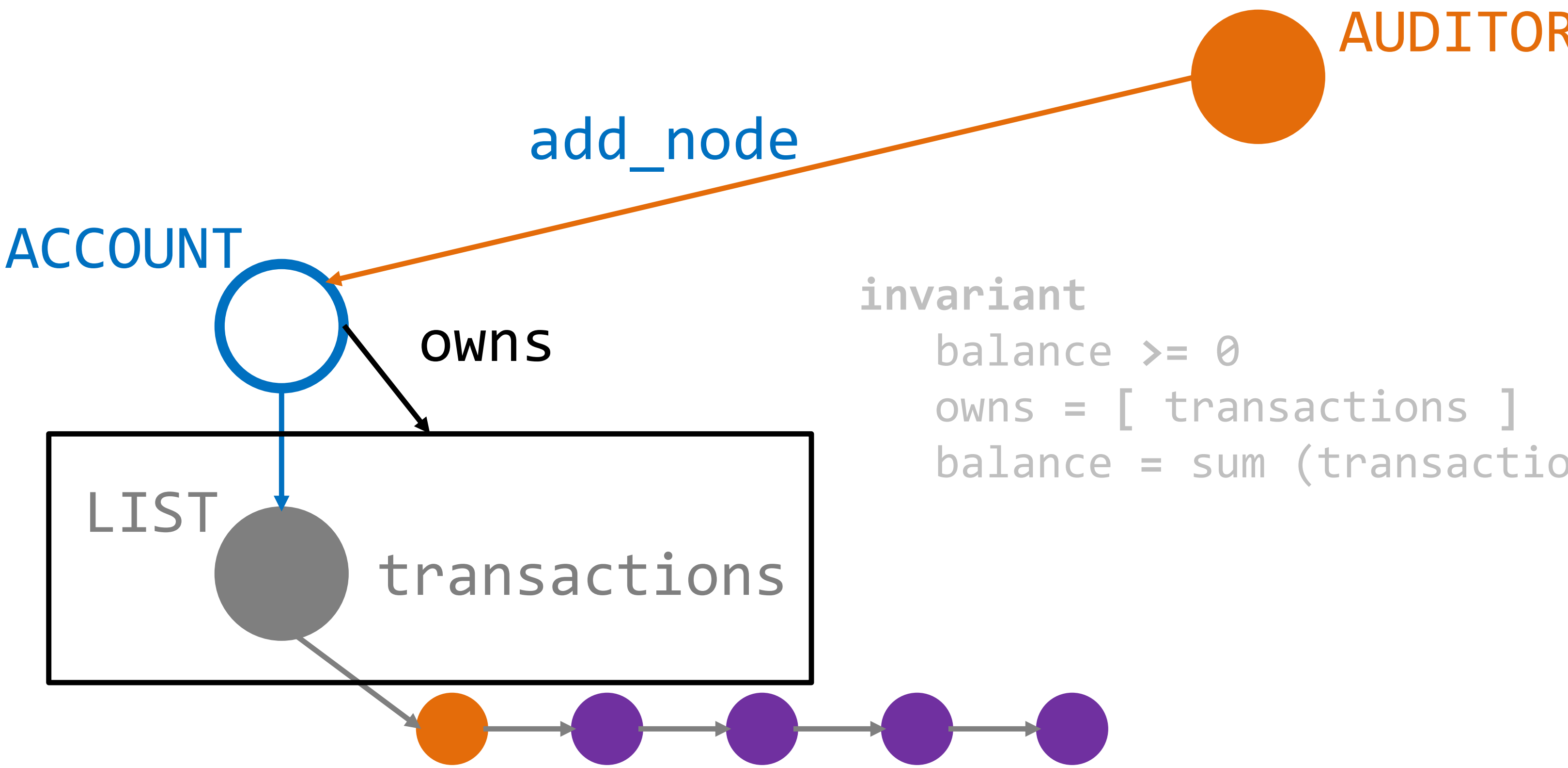


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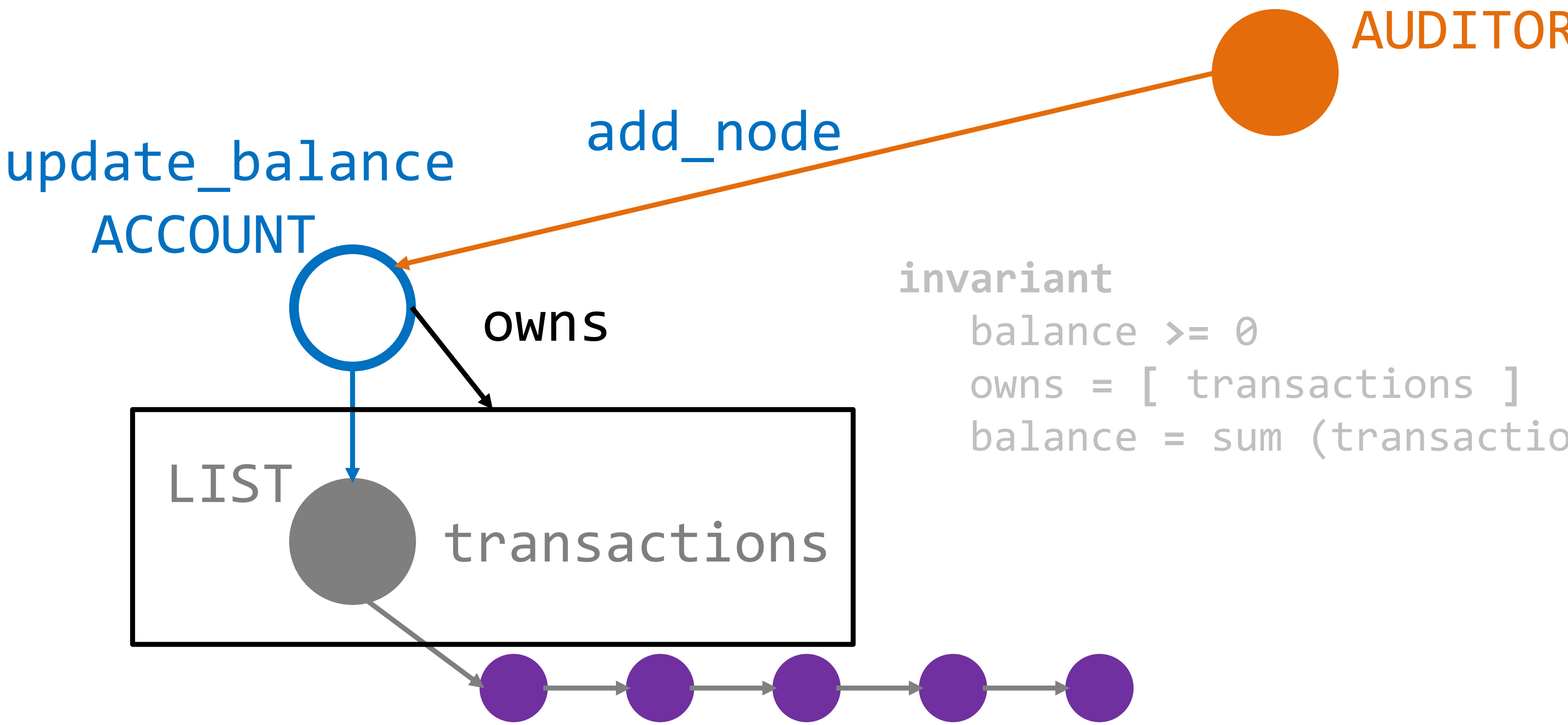


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Ownership

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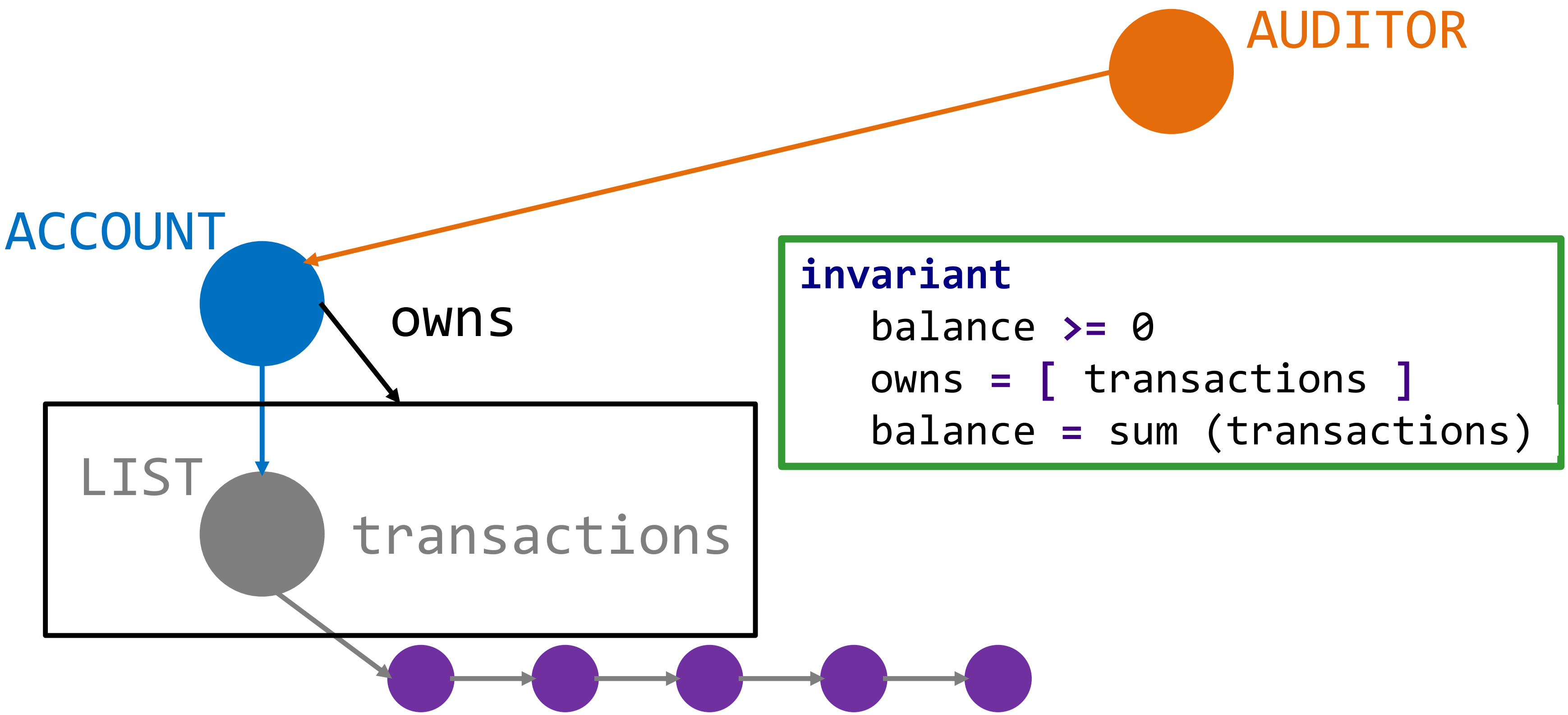


Demo: ownership in AutoProof

AutoProof verifies `deposit` and `withdraw` in ACCOUNT with an owned list of transactions

```
transactions: SIMPLE_LIST [INTEGER]
  -- History of transactions:
  --   positive integer = deposited amount
  --   negative integer = withdrawn amount
  --   latest transactions in back of list
```

Follow this demo at:

http://comcom.csail.mit.edu/e4pubs/#demo-key

(Tab account_ownership.e)

Wrapping and unwrapping

Combination on ownership and invariants:

Wrapped object = closed and not owned

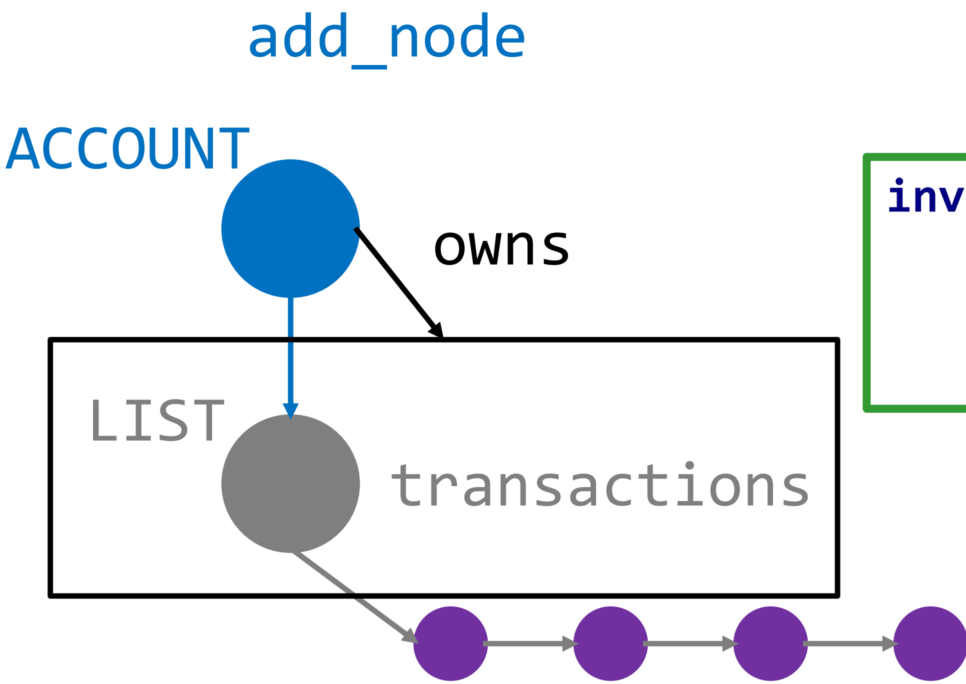
Unwrapped object = open (or owned)

	WRAPPED	UNWRAPPED
Invariant:	holds	may not hold
Clients:	any object	within owner
Modifications:	modify after unwrapping	wrap after modifying

Wrapping and unwrapping

Typical modification pattern:

unwrap, modify, wrap (check consistency)

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invariant
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    balance = sum (transactions)
```

Wrapping and unwrapping

Typical modification pattern:

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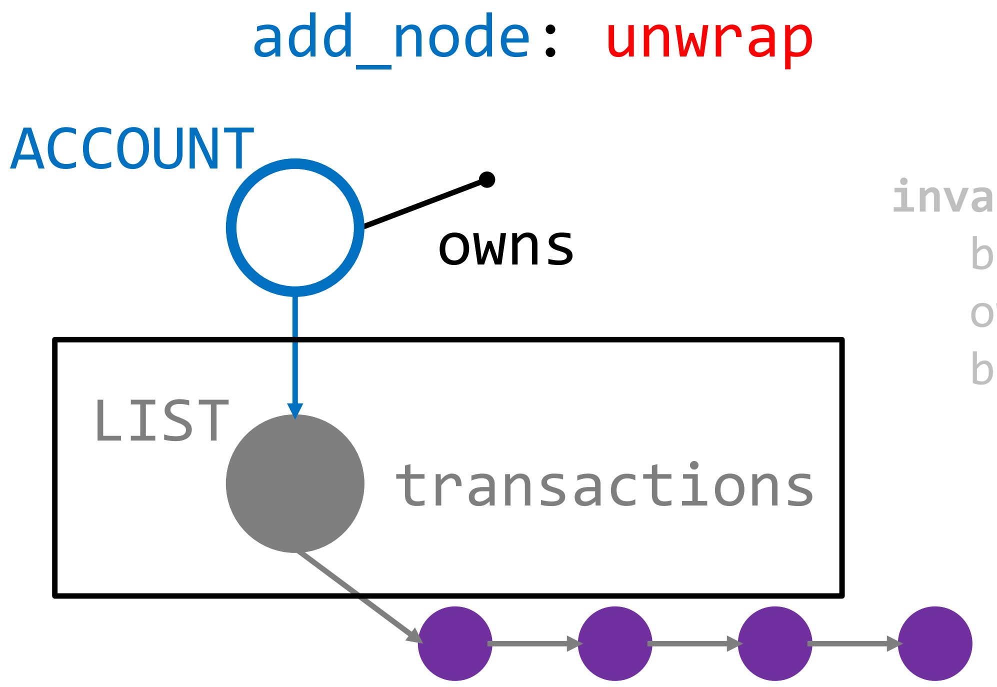


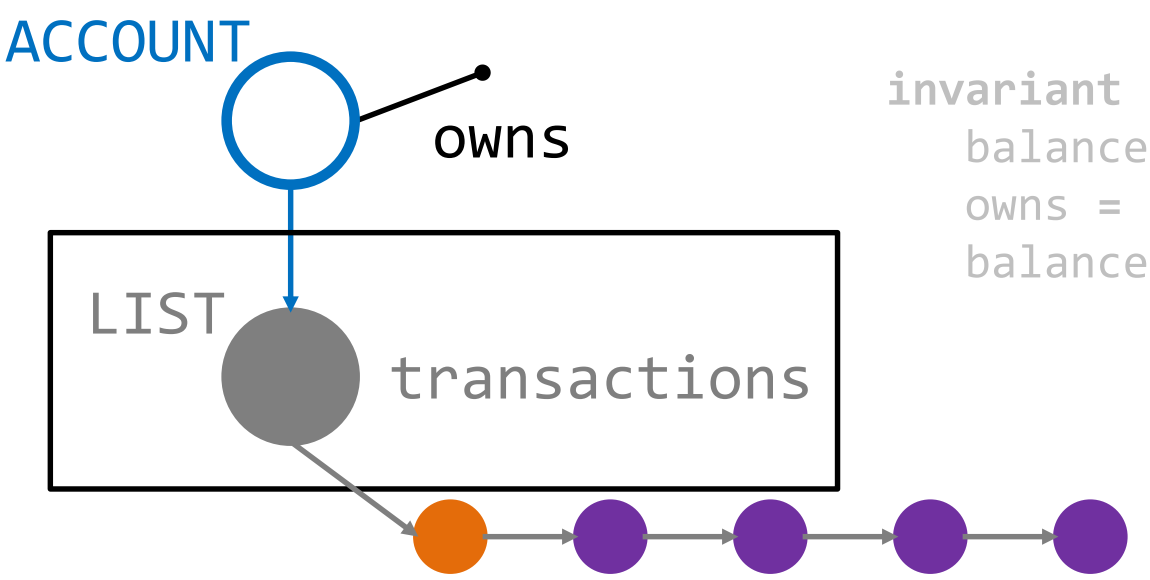

```
invariant
   balance >= 0
   owns = [ transactions ]
   balance = sum (transactions)
```

Wrapping and unwrapping

Typical modification pattern:

unwrap, modify, wrap (check consistency)

```
add_node: unwrap; modify
```



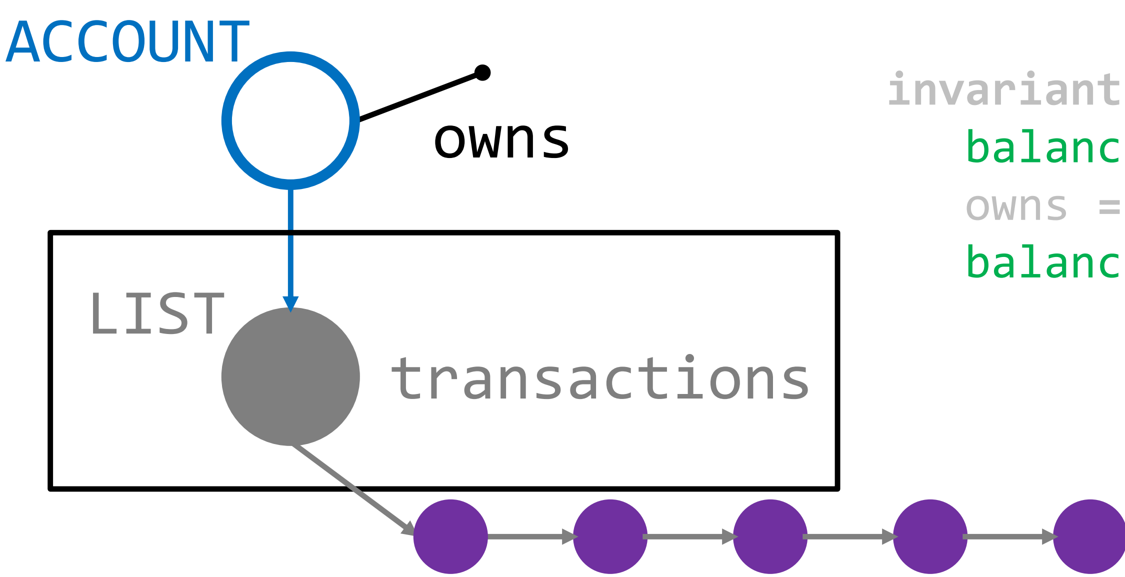

```
invariant
   balance >= 0
   owns = [ transactions ]
   balance = sum (transactions)
```

Wrapping and unwrapping

Typical modification pattern:

unwrap, modify, wrap (check consistency)

```
add_node: unwrap; modify; wrap (check)
```



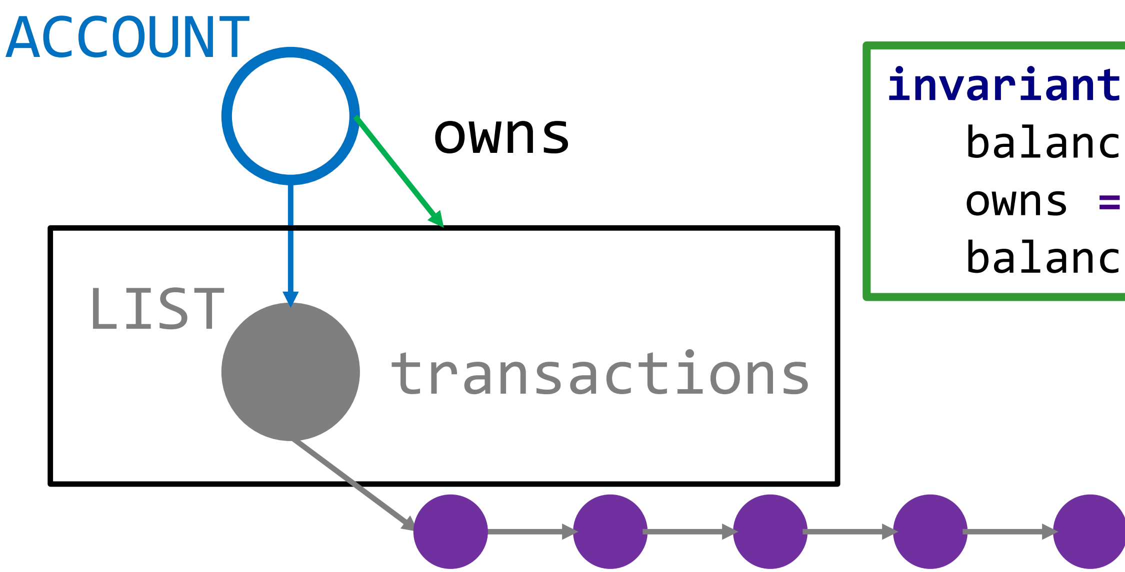

```
invariant
   balance >= 0
   owns = [ transactions ]
   balance = sum (transactions)
```

Wrapping and unwrapping

Typical modification pattern:

unwrap, modify, wrap (check consistency)

`add_node: unwrap; modify; wrap (check)`




```
invariant
    balance >= 0
    owns = [ transactions ]
    balance = sum (transactions)
```

Demo: ownership preserves stability

Ownership achieves stability when leaking references to the internal `transactions` list in ACCOUNT

```
leak_transactions: SIMPLE_LIST [INTEGER]

leak_transactions_unsafe: SIMPLE_LIST [INTEGER]
```

Follow this demo at:

http://comcom.csail.mit.edu/e4pubs/#demo-key

(Tabs account_ownership.e and auditor.e)

Semantic collaboration

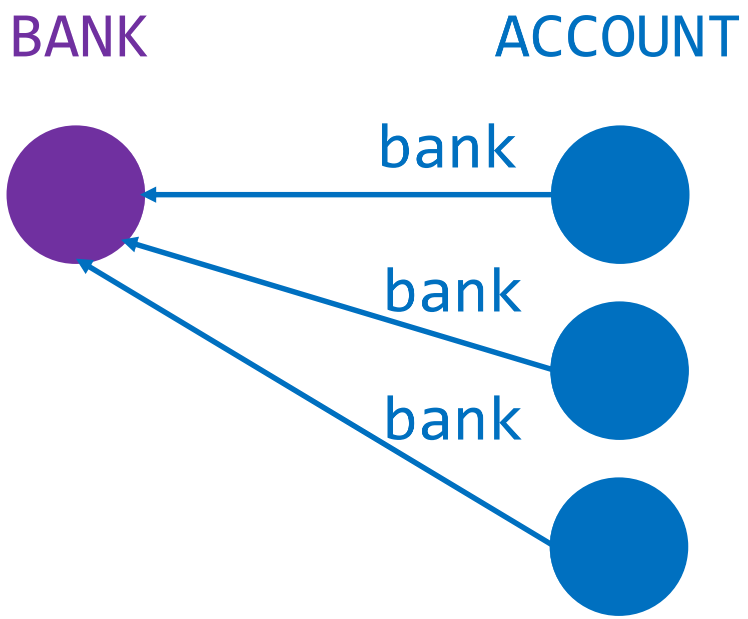
For collaborative object structures, AutoProof offers a novel protocol: semantic collaboration


```
invariant

   interest_rate = bank.rate
```

Semantic collaboration

For collaborative object structures, AutoProof offers a novel protocol: semantic collaboration

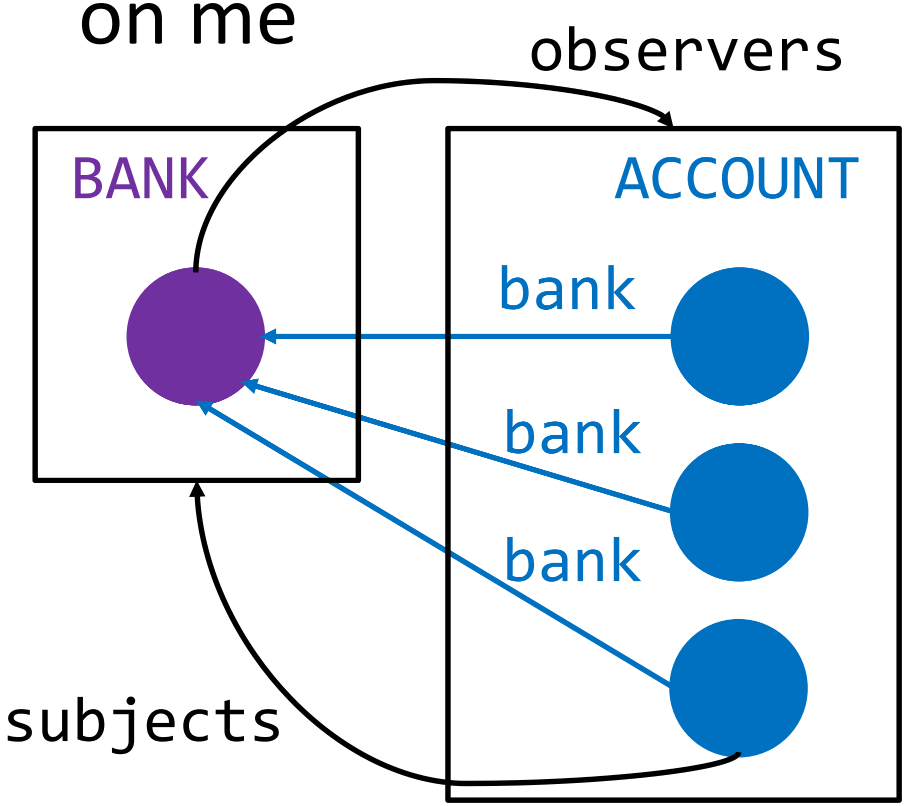



```
invariant

   interest_rate = bank.rate
```

Semantic collaboration

- Subjects = objects my consistency depends on
- Observers = objects whose consistency depends on me



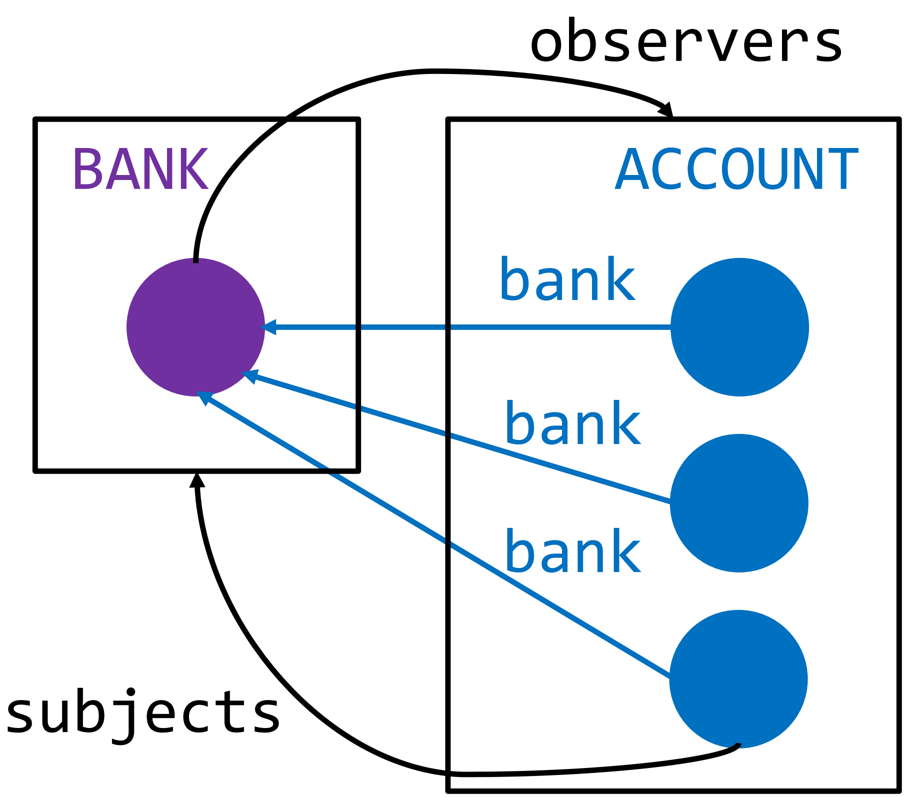

```
invariant
    subjects = [ bank ]
    Current in bank.observers
        -- Implicit in AutoProof

    interest_rate = bank.rate
```

Semantic collaboration

The bank changes the rate (and notifies accounts)

update

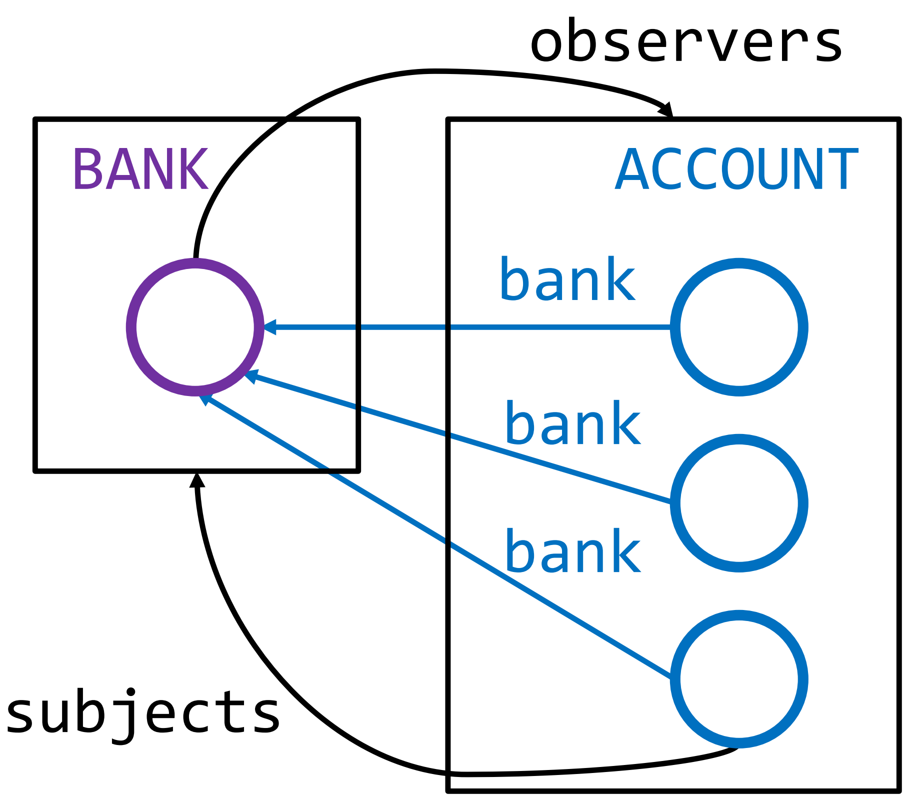



```
invariant
    subjects = [ bank ]
    Current in bank.observers
    interest_rate = bank.rate
```

Semantic collaboration

The bank changes the rate (and notifies accounts)

```
update: open bank, observers
```

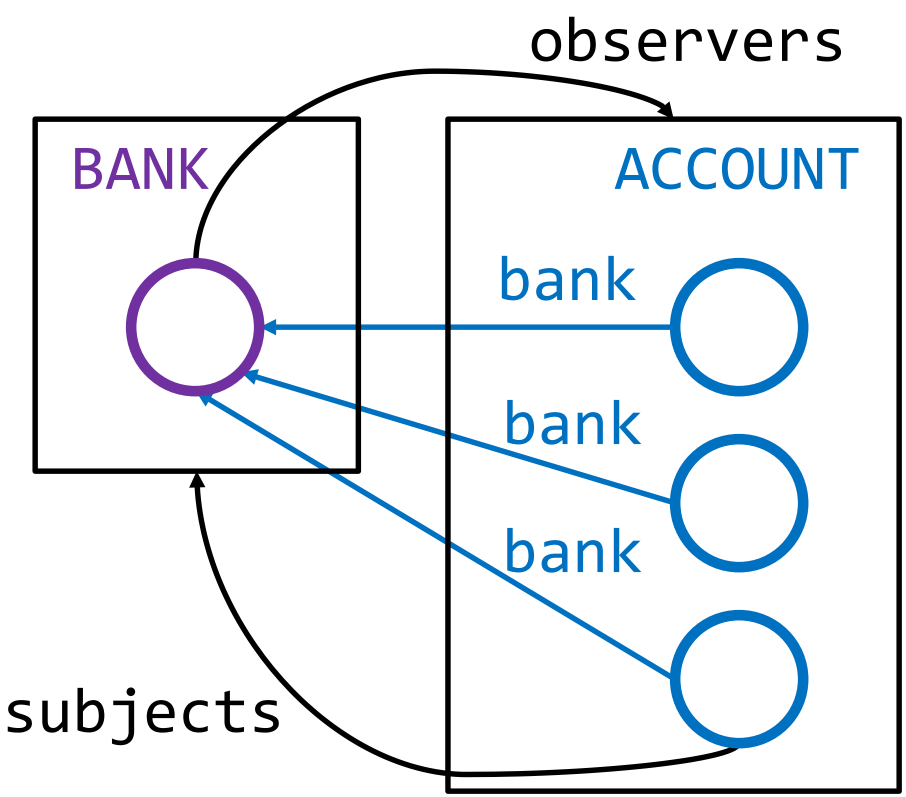



```
invariant
    subjects = [ bank ]
    Current in bank.observers
    interest_rate = bank.rate
```

Semantic collaboration

The bank changes the rate (and notifies accounts)

```
update: set rate
```

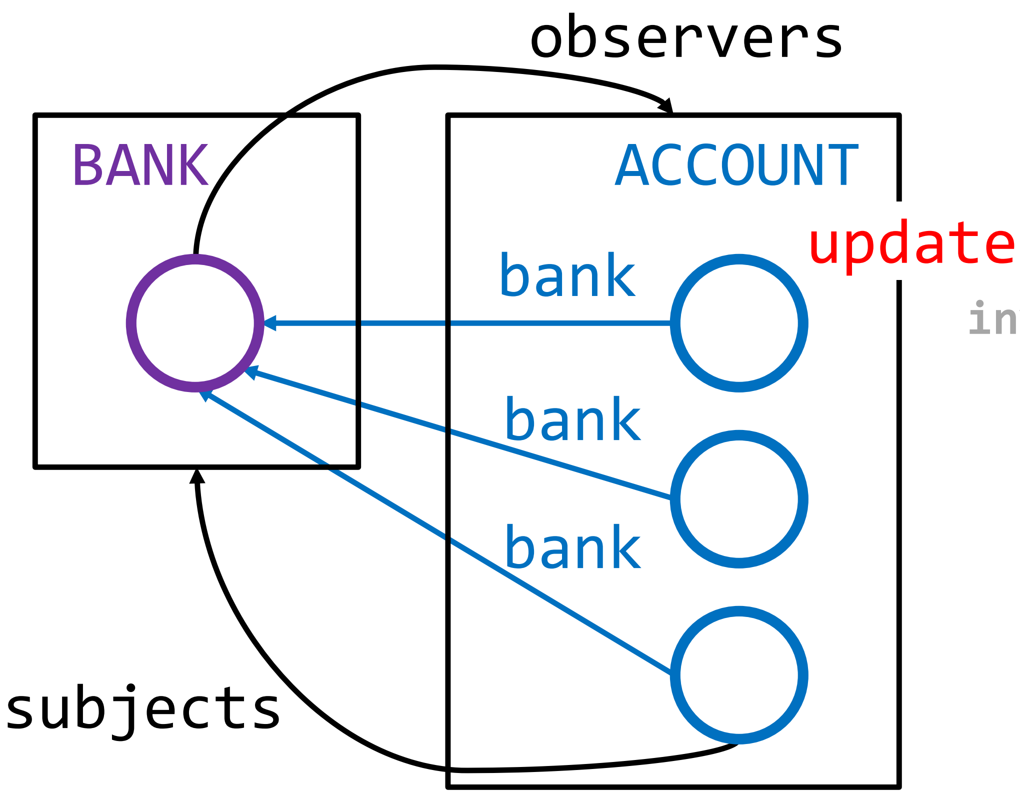



```
invariant
    subjects = [ bank ]
    Current in bank.observers
    interest_rate = bank.rate
```

Semantic collaboration

The bank changes the rate (and notifies accounts)

```
update: set rate, notify all accounts
```

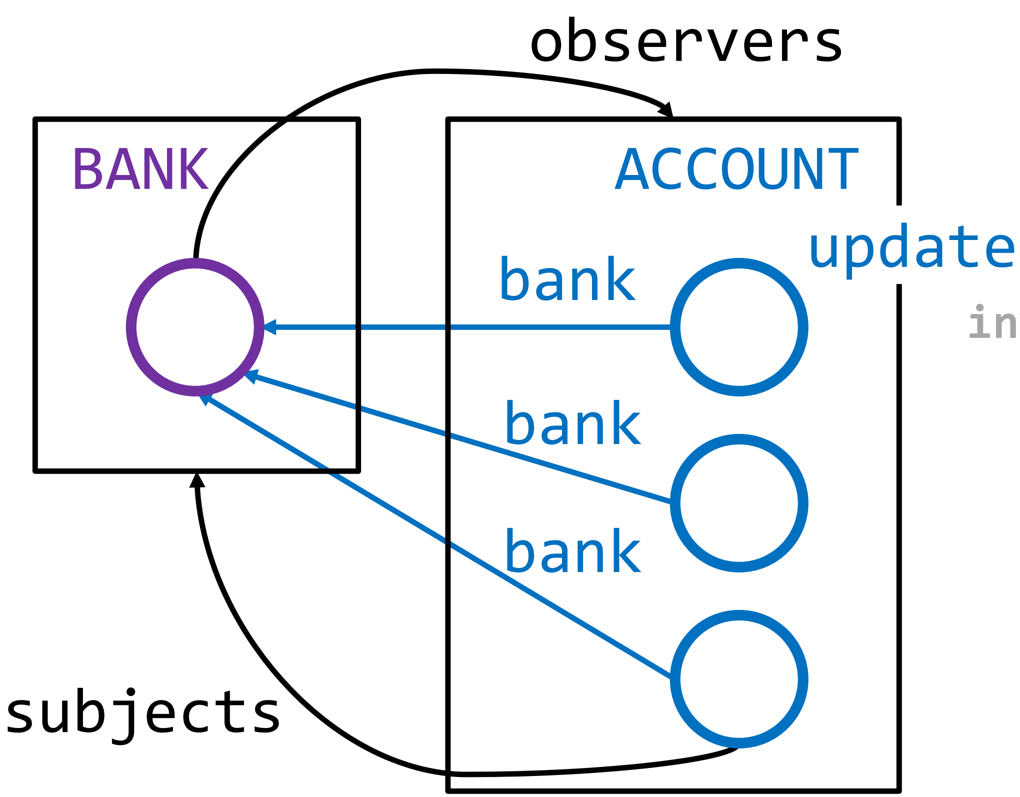



```
invariant
    subjects = [ bank ]
    Current in bank.observers
    interest_rate = bank.rate
```

Semantic collaboration

The bank changes the rate (and notifies accounts)

```
update: set rate, notify all accounts
```

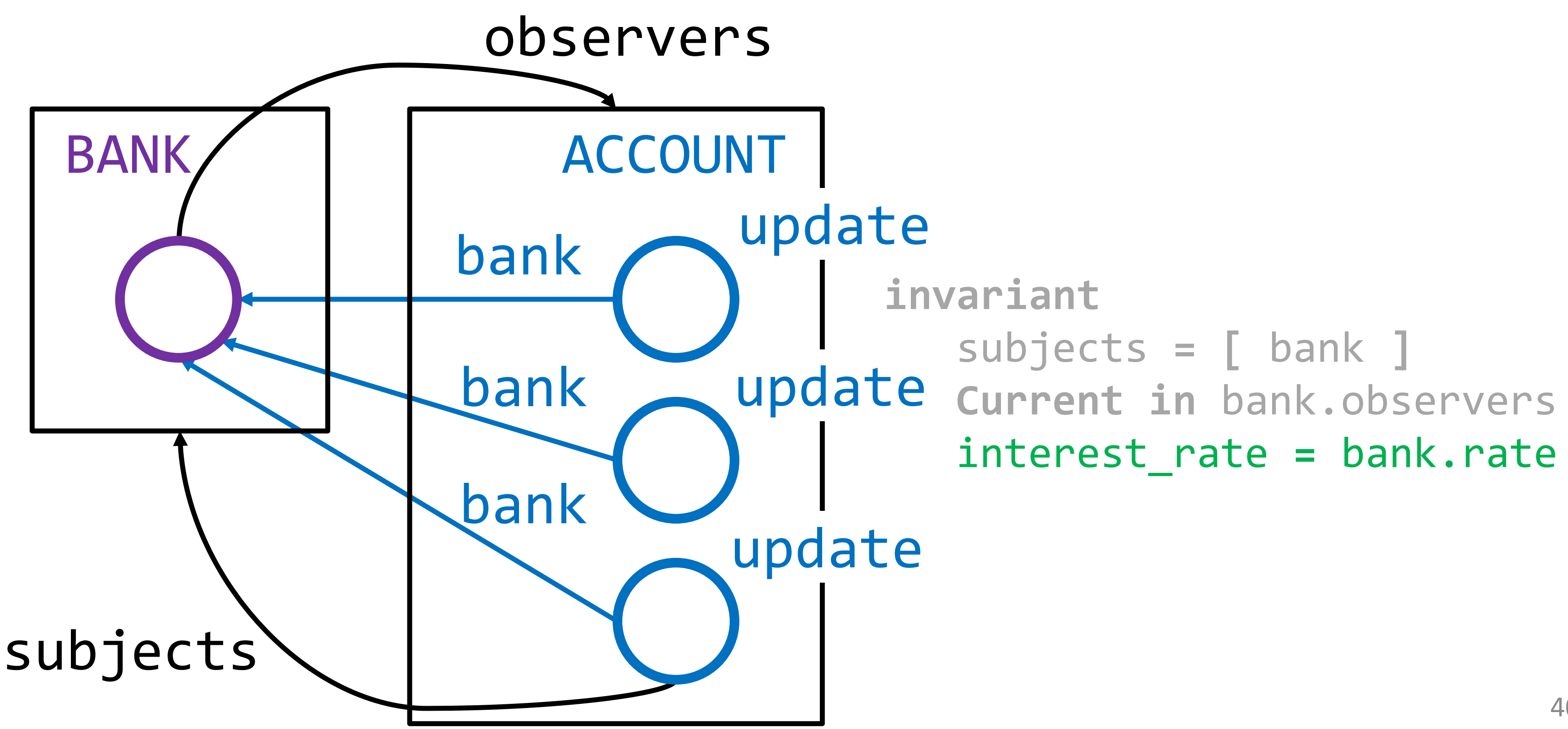



```
invariant
    subjects = [ bank ]
    Current in bank.observers
    interest_rate = bank.rate
```

Semantic collaboration

The bank changes the rate (and notifies accounts)

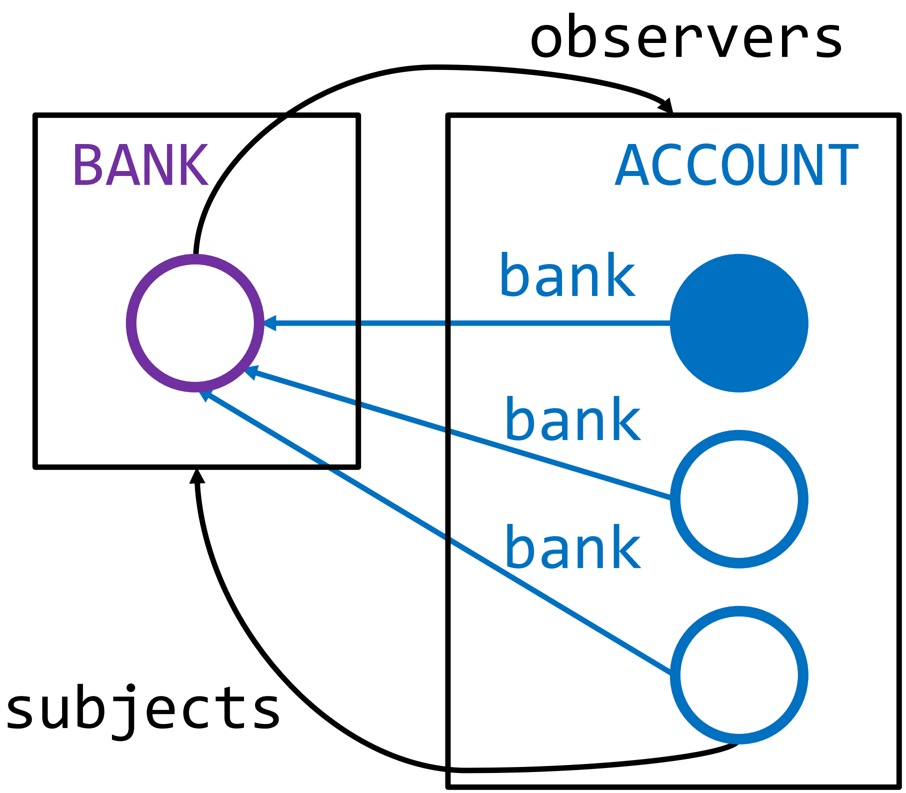
`update: set rate, notify all accounts`



Semantic collaboration

The bank changes the rate (and notifies accounts)

`update: wrap bank, all observers (check)`

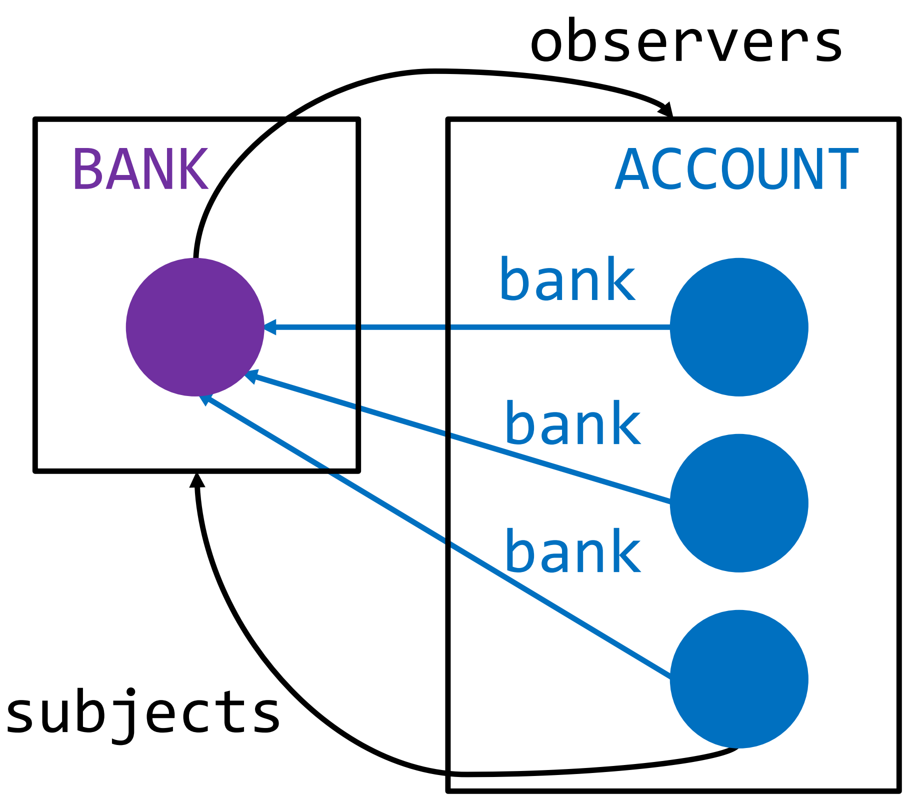



```
invariant
    subjects = [ bank ]
    Current in bank.observers
    interest_rate = bank.rate
```

Semantic collaboration

The bank changes the rate (and notifies accounts)

`update: open, modify, wrap (check)`




```
invariant
    subjects = [ bank ]
    Current in bank.observers
    interest_rate = bank.rate
```

Demo: collaboration in AutoProof

AutoProof verifies `update_rate` in ACCOUNT and `change_master_rate` in BANK based on semantic collaboration features

```
subjects_definition: subjects = [ bank ]
consistent_rate: interest_rate = bank.master_rate
```

Follow this demo at:

http://comcom.csail.mit.edu/e4pubs/#demo-key

(Tabs account_collaboration.e and bank.e)

Wrapping and unwrapping

In hierarchical structures there is one typical modification pattern:

unwrap, modify, wrap (check consistency)

In collaborative structures, there is more flexibility:

- unwrap, modify, wrap
- unwrap, modify, leave open (invalidate)
- share responsibility for restoring consistency between subjects and observers

Data structures

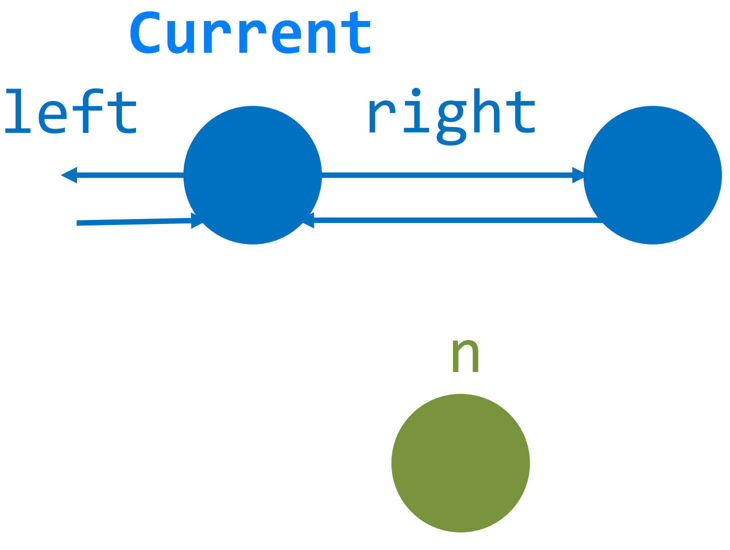
The features of semantic collaboration work well to reason about data structure implementations.

Data structures: doubly-linked list

As an example, let's outline node insertion in a doubly-linked list:

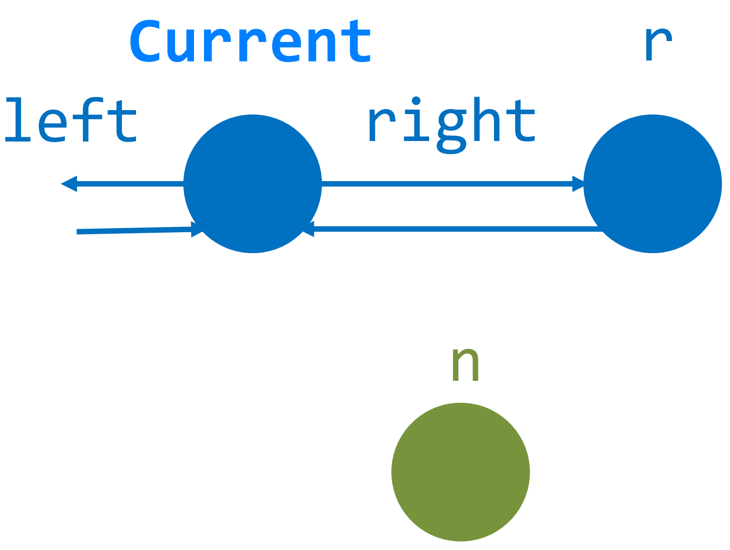
- A singly linked list is hierarchical: the head controls access to the whole list.
- A (circular) doubly-linked list is collaborative: every node depends on its neighbors, and they depend on it

Insert node n to right of Current



Insert node n to right of `Current`

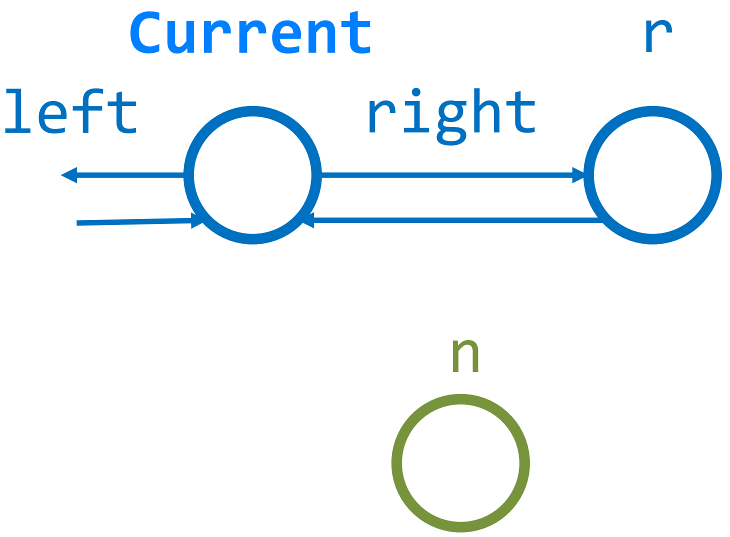
```
var r := right
```



Insert node n to right of **Current**

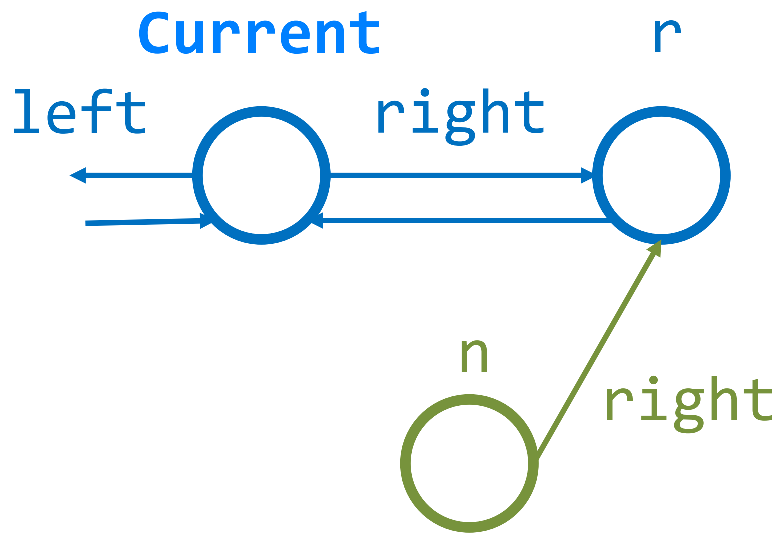
```
var r := right

unwrap Current, r, n
```



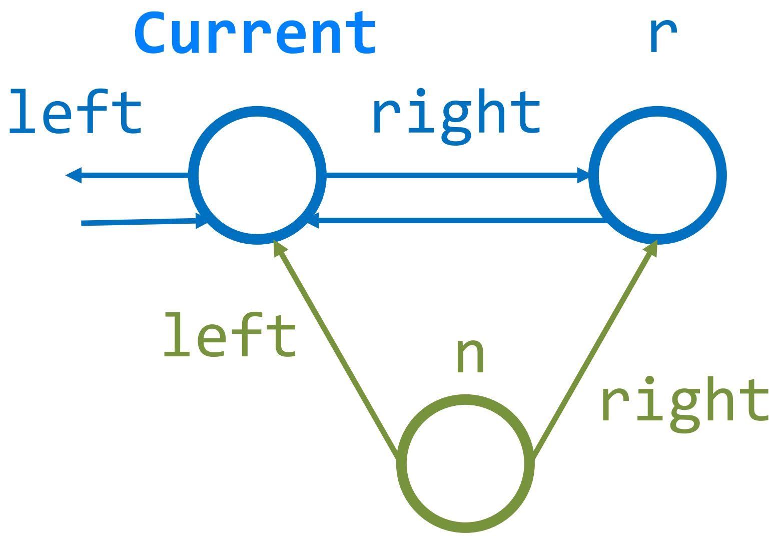
Insert node n to right of Current

```
var r := right
unwrap Current, r, n
n.right := r
```



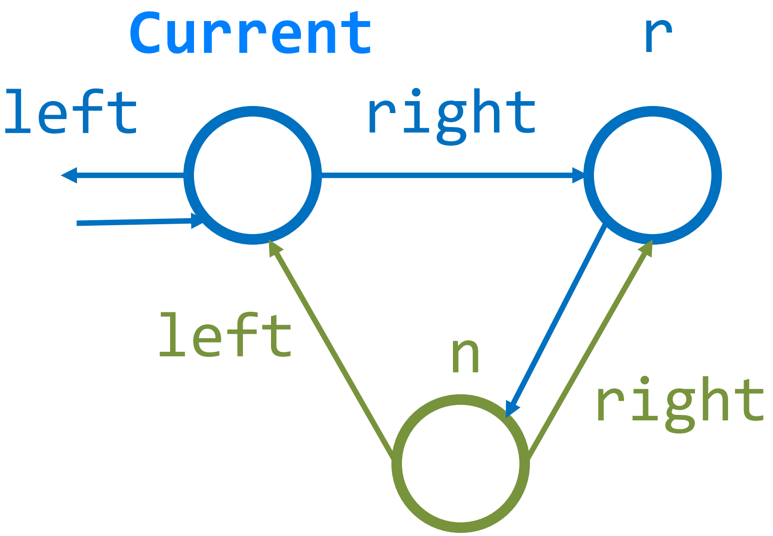
Insert node n to right of Current

```
var r := right
unwrap Current, r, n
n.right := r
n.left := Current
```



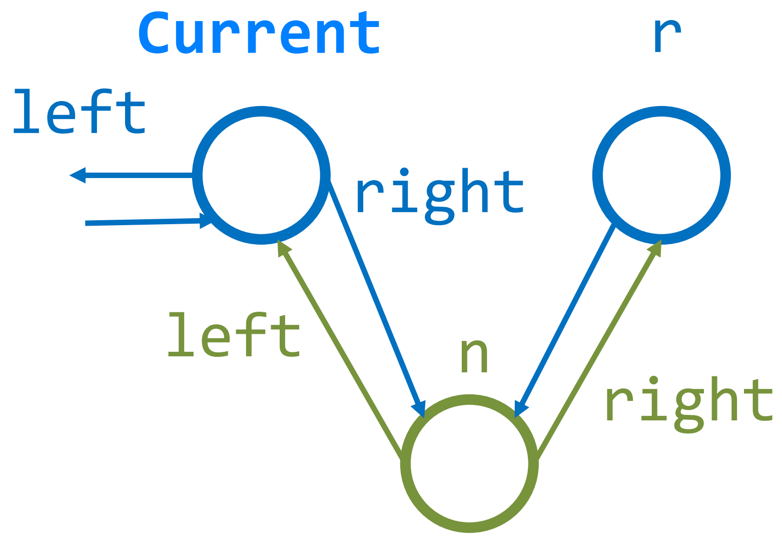
Insert node n to right of Current

```
var r := right
unwrap Current, r, n
n.right := r
n.left := Current
r.left := n
```



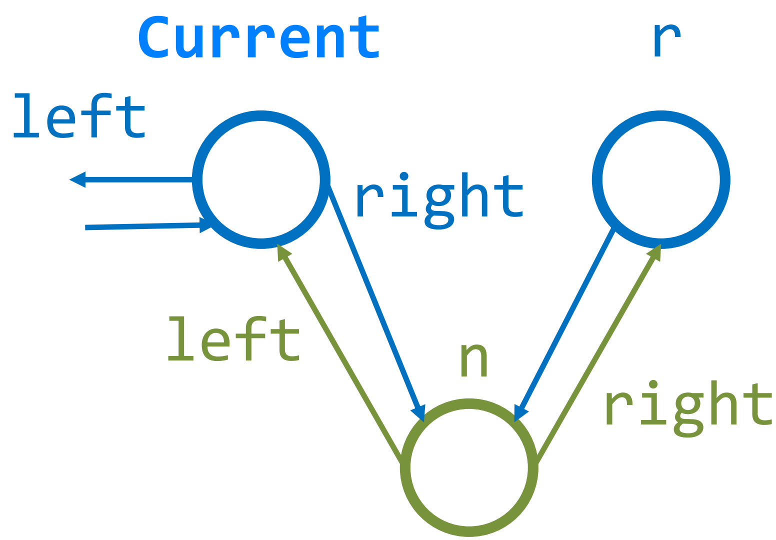
Insert node n to right of Current

```
var r := right
unwrap Current, r, n
n.right := r
n.left := Current
r.left := n
right := n
```



Insert node n to right of Current

```
var r := right
unwrap Current, r, n
n.right := r
n.left := Current
r.left := n
right := n
n.subjects, n.observers := [r, Current]
subjects, observers := [left, n]
r.subjects, r.observers := [n, r.right]
```



Insert node n to right of Current

```
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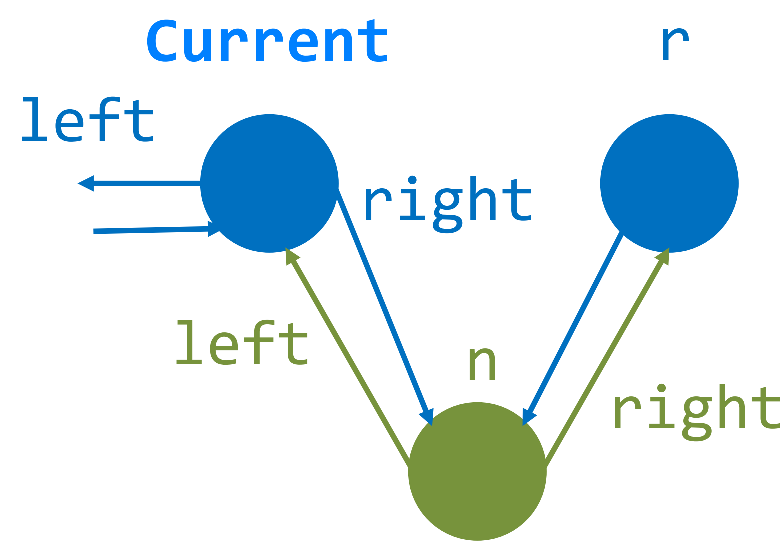
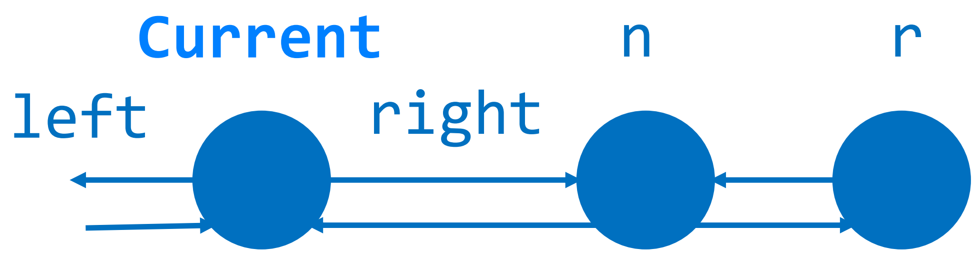
unwrap Current, r, n
n.right := r
n.left := Current
r.left := n
right := n
n.subjects, n.observers := [r, Current]
subjects, observers := [left, n]
r.subjects, r.observers := [n, r.right]
wrap Current, r, n
```



Insert node n to right of Current

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n.right := r
n.left := Current
r.left := n
right := n
n.subjects, n.observers := [r, Current]
subjects, observers := [left, n]
r.subjects, r.observers := [n, r.right]
wrap Current, r, n
```

Attribute update guards

Who’s responsible for checking that an update to an attribute satisfies the invariant?

```
a: A guard: g(a’, o)
```

- every observer `o` of `Current` that satisfies the guard `g` is responsible for checking that updating `Current`’s attribute `a` to the value `a’` does not violate the invariant of `o`

Update guards in doubly-linked list

```
right: NODE guard: o /= right
```

When changing the value of attribute `right`:

- the `left` node checks that its invariant is not violated by changing `right` in the current node
  - the `left` node's invariant does not depend on `Current.right` (it remains wrapped)
- the current node checks that `right`'s invariant is not violated by changing `Current.right`
  - the `right` node is open when changing `Current.right` (invariant vacuously holds)
  - actual check performed when wrapping `right`

Demo: doubly-linked list

AutoProof verifies class NODE, representing the generic node of a doubly-linked list

```
insert_right (n: NODE)
    -- Insert n to the right of Current.
```

Follow this demo at:

http://comcom.csail.mit.edu/e4pubs/#demo-key

(Tab node.e)

Proving realistic implementations

Semantic collaboration is part of a verification framework with features suitable to reason about realistic implementations:

- model-based specifications
  - completeness
- extensible specification types and MML library
- (abstract) framing with inheritance
- modular verification with inheritance
  - nonvariant, covariant methods
- finely-tuned encoding in AutoProof

AutoProof on realistic software

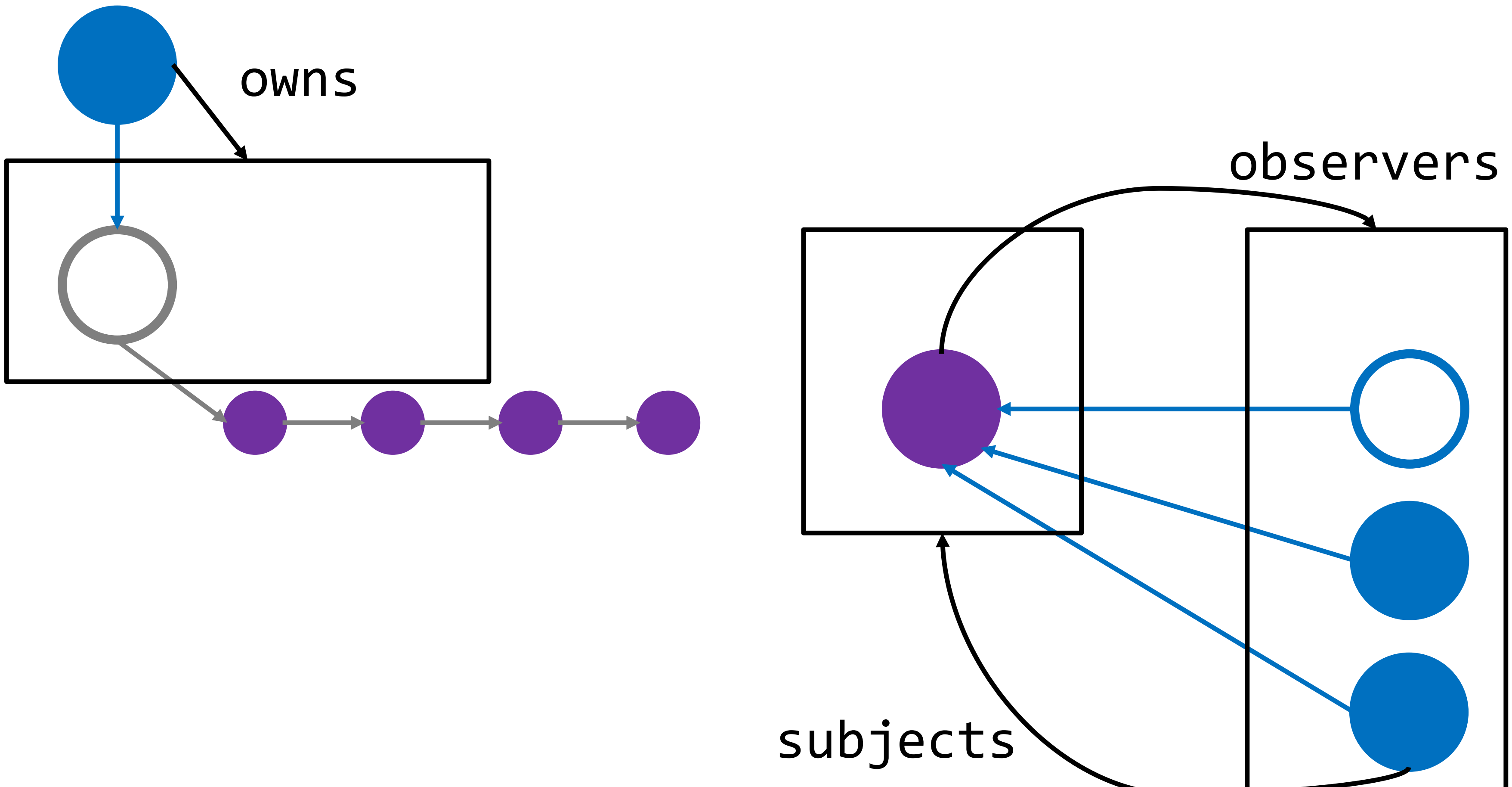
Verification benchmarks:

# programs	LOC	SPEC/CODE	Verification time
25	4400	Lines: 1.0 Tokens: 1.9	Total: 3.4 min Longest method: 12 sec Average method: < 1 sec

EiffelBase2 – a realistic container library:

# classes	LOC	SPEC/CODE	Verification time
46	8400	Lines: 1.4 Tokens: 2.7	Total: 7.2 min Longest method: 12 sec Average method: < 1 sec

Class-invariant based reasoning with semantic collaboration



[VSTTE ‘13, FM ‘14, TACAS ‘15, FM ‘15, STTT ‘16]