Reasoning about External Calls using Object Capabilities

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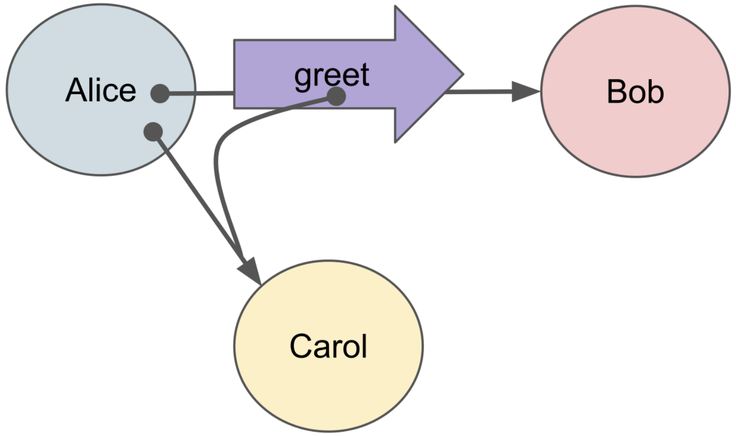


James Noble

Susan Eisenbach

Julian Mackay

The Problem

External and Internal Code is tightly intertwined.

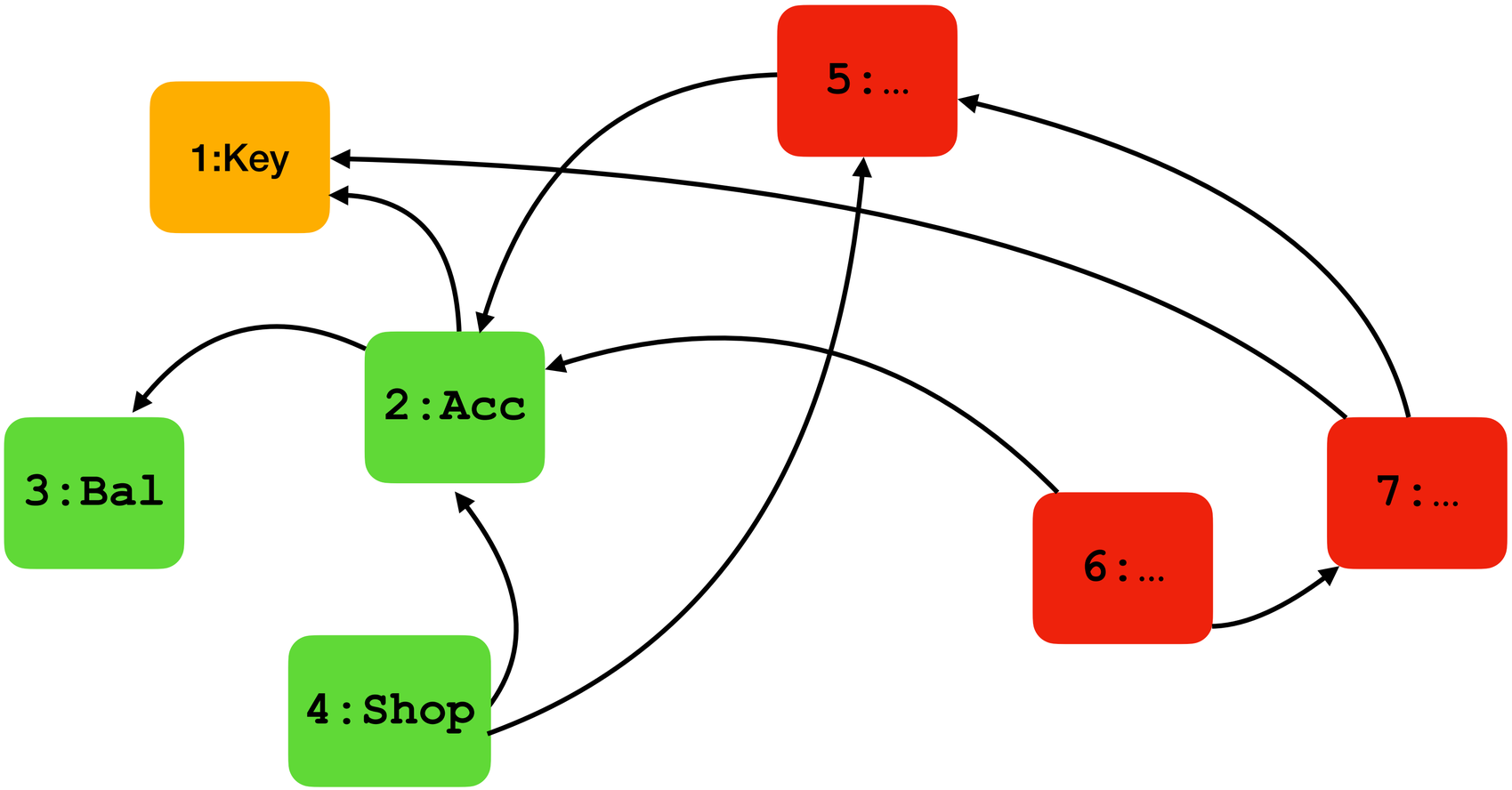
Object Capabilities used to control External Effects

Our Remit

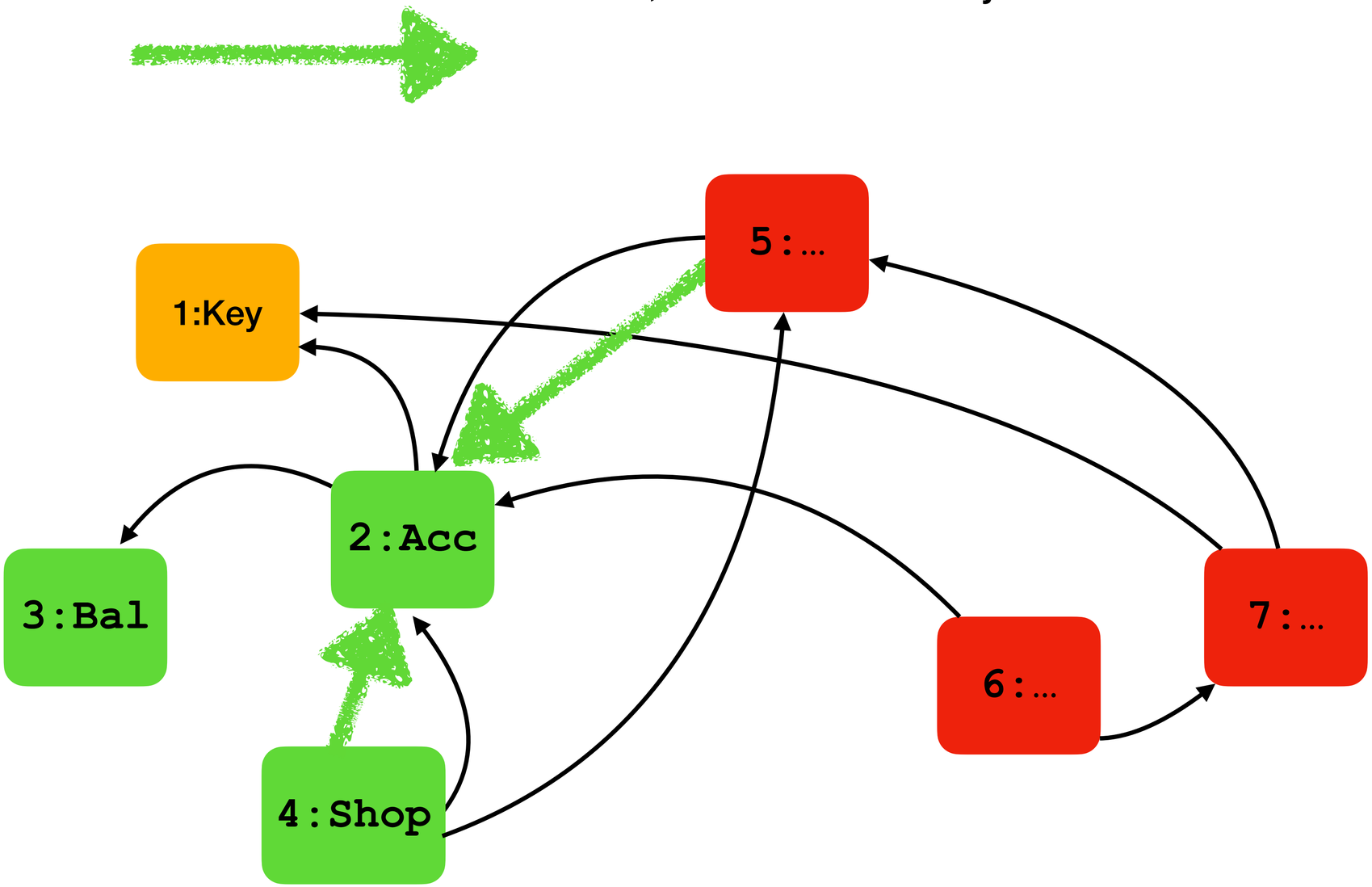
Reason about Object Capabilities controling Effects:
1) Specification, 2) Verification

Internal (trusted) and External (untrusted) objects are intertwined.

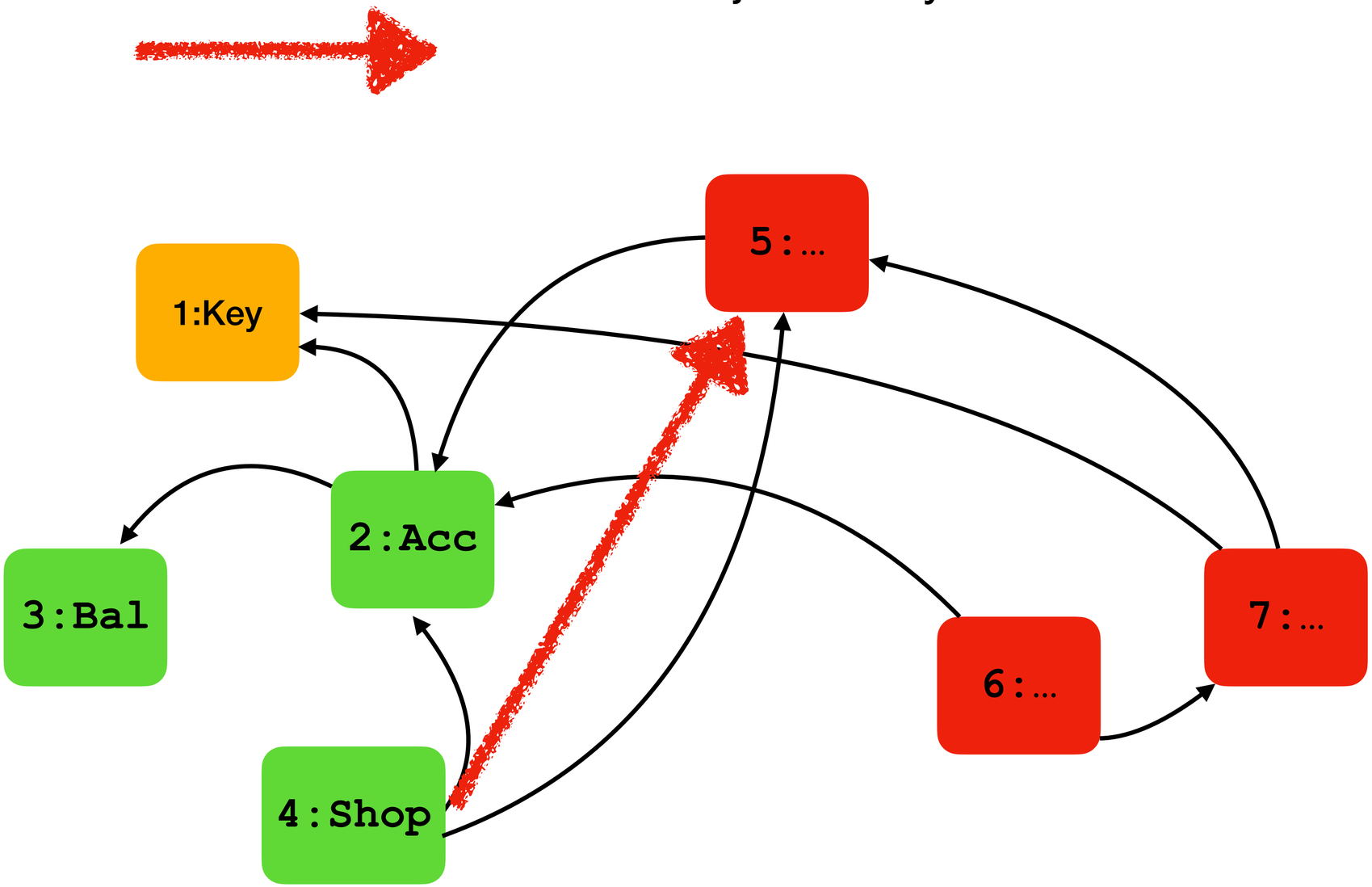
Capability objects (ocap) **are necessary** for certain effects.

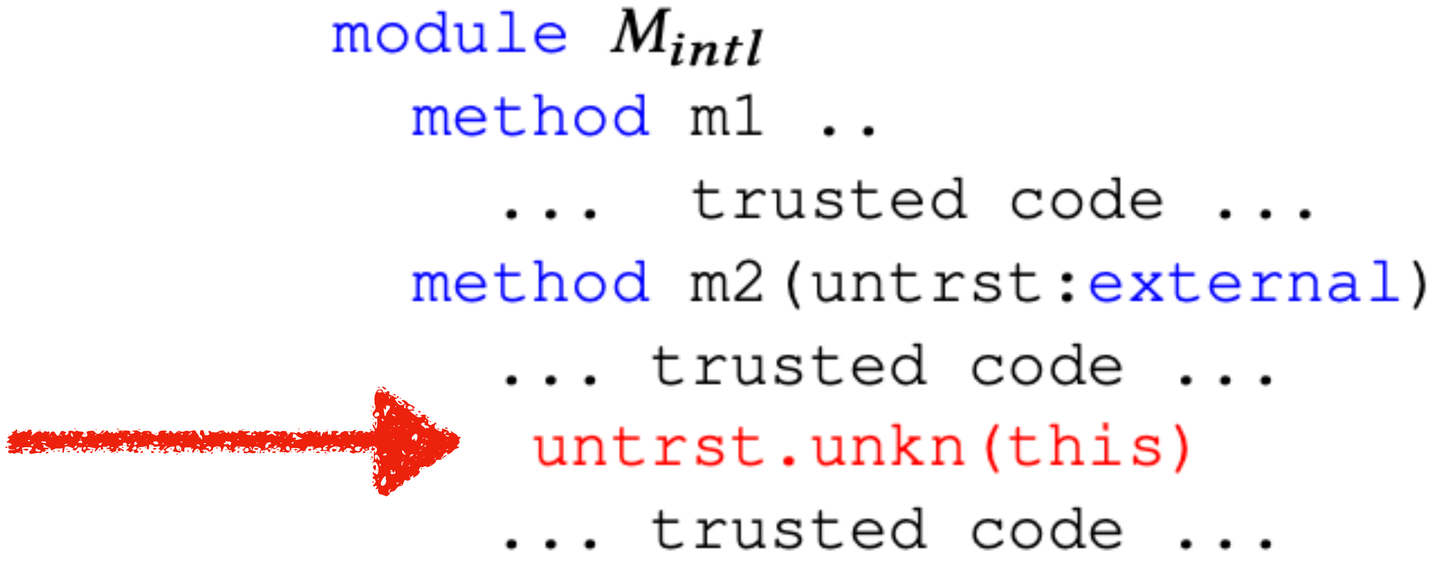


Internal Calls: Internal, or external objects call methods on internal objects.



External Calls: Internal objects may call methods on external objects.





What are the possible effects at the external call?

1) Some effects will **never** happen cf. object invariants

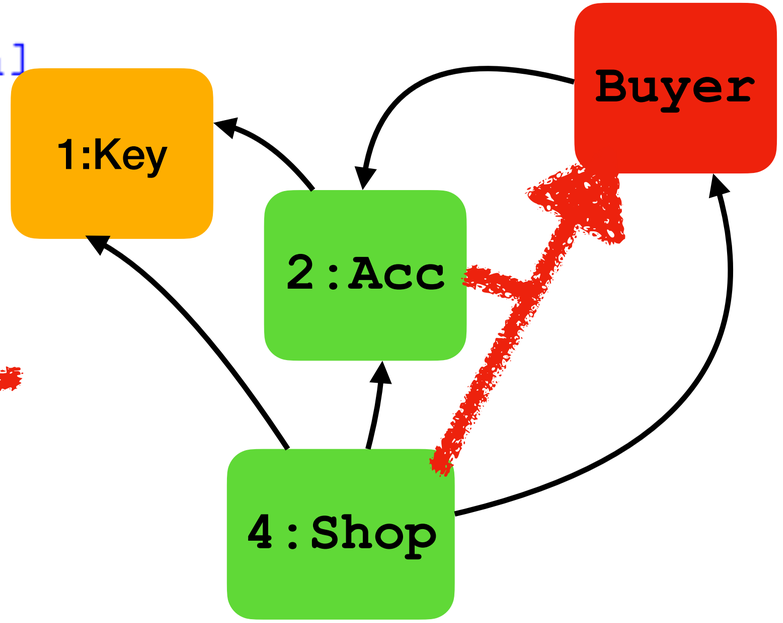
2) Some effects **may** happen — *but only if* external access to certain capabilities.

Our Work

```
class Shop

  field accnt:Account, invntry:Inventory, clients:external

  public method buy(buyer:external, anItem:Item)
     int price = anItem.price
     int oldBlnce = this.accnt.blnce
     buyer.pay(this.accnt, price)
     if (this.accnt.blnce == oldBlnce+price)
        this.send(buyer,anItem)
     else
        buyer.tell("you have not paid me")
```



What are the possible effects at the external call?

Q Can buyer steal money from the shop's account?

A No, if a) Money not reduced unless external access to account's key

b) Buyer has no access to account's key

c) Module does not leak the account's key

Some effects **may** happen — *but only if* some condition/access to ocap

1st Attempt

A ::= … | A->A | **will**<A> | **was**<A> | **ext**<e> | **acc**<e,e'>

2nd Attempt

No logic

A ::= … | A->A | **ext**<e> | **acc**<e,e'>

S ::= **from** A_{pre} **to** Apost **onlyIf** A_{nec} |
from A_{pre} **to** Apost **onlyThrough** A_{nec}

Logic,
only internal calls

Current Attempt

A ::= … | **ext**<e> | **prot**<e> | **prot**<e,e'>

S ::= ¬ A ∧ ¬ A_{nec} "is invariant"

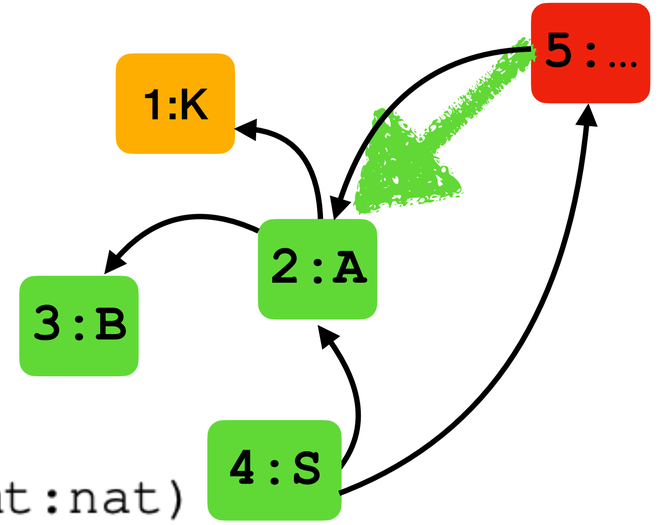
Logic,
external calls

The Account example in Code

(fields are private)

Three Modules

```
module M_good
  class Shop    ... as earlier ...
  class Account
    field blnce:int
    field key:Key
    public method transfer(dest:Account, key':Key, amt:nat)
       if (this.key==key')  this.blnce-=amt; dest.blnce+=amt
    public method set(key':Key)
       if (this.key==null)  this.key=key'
```




```
module M_bad
  ... as earlier ...
  public method set(key':Key)
    this.key=key'
```

```
module M_fine
  ... as earlier ...
  public method set(key',key'':Key)
    if (this.key==key') this.key=key''
```

The trouble is … the emergent behaviour

M_{bad}

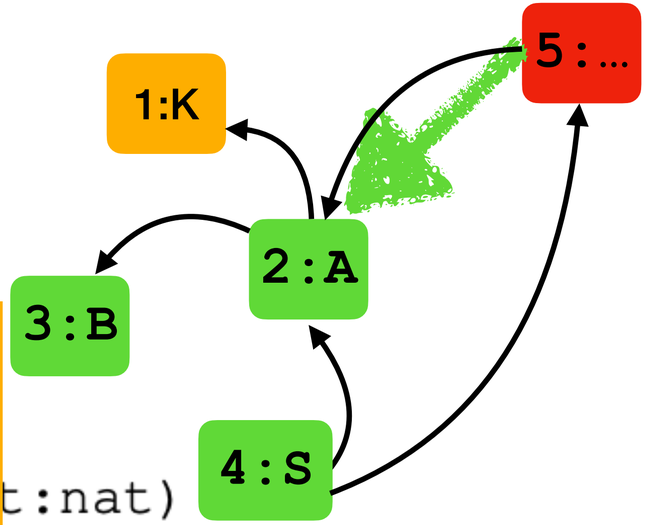
1) Attacker calls `set(…)` and changes the password
2) Attacker calls `transfer(…)` and uses password to withdraw money

Parity MultiSig Wallet Hack (150,000 ETH (~30M USD) 2017)

1) Attacker calls `initWallet(…)` and makes themselves the single owner
2) Attacker calls `execute(…)` and withdrawns all funds

Three Modules

```
module Mgood
  class Shop    ... as earlier ...
  class Account
    field blnc
    field key:
    public met                                    t:nat)
       if (thi                                    ce+=amt
    public met
       if (thi
```



Remit_1: A module spec S, such that

$M_{good} \models S$

$M_{bad} \not\models S$

$M_{fine} \models S$

```
module Mbad
  ... as earlier ...
  public method set(key':Key)
    this.key=key'
```

```
module Mfine
  ... as earlier ...
  public method set(key',key'':Key)
    if (this.key==key') this.key=key''
```

Three Modules

```
module Mgood
  class Shop    ... as earlier ...
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    field blnc
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       if (thi
```
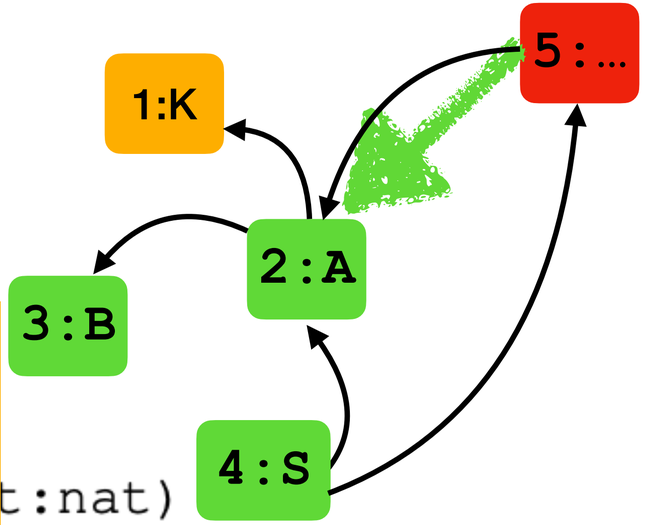



Remit_2: An inference system with which to prove

$M_{good} \vdash S$

$M_{bad} \nvdash S$

$M_{fine} \vdash S$

```
module Mbad
  ... as earlier ...
  public method set(key':Key)
    this.key=key'
```

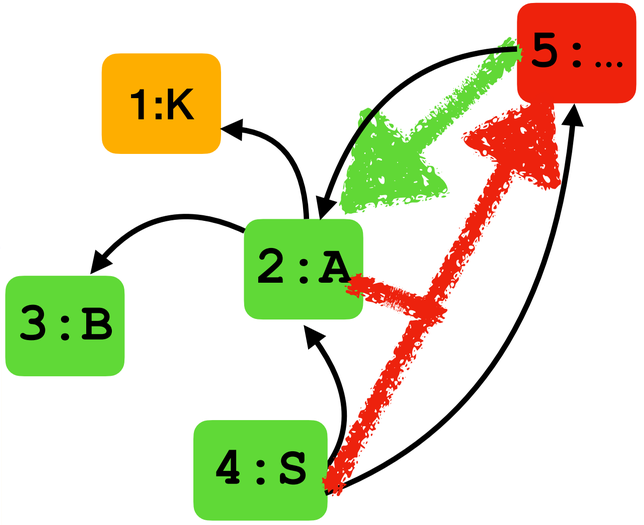
```
module Mfine
  ... as earlier ...
  public method set(key',key'':Key)
    if (this.key==key') this.key=key''
```

Three Modules

```
class Shop

  field accnt:Account, invntry:Inventory, clients:external

  public method
    int price =
    int oldBlnc
    buyer.pay(t
    if (this.ac
       this.sen
    else
       buyer.te
```

Remit_3: An inference system with which to prove

external calls



If a) `Account` comes from a “good” module, and
b) `buyer` has no “unprotected” access to `4.accnt.pwd`,
then
`buyer.payme(..)` will not decrease `4.accnt.blnce`,

In Summary

External Objects

- may have access to internal objects
- may execute arbitrary code
- may invoke any public internal method
- may collude with one another
- may *not* directly read/write internal fields

Our Specifications

- guarantee that certain effects happen only under certain condtions
- In genereal do *not* preclude these conditions

Remit_1: A specification language,

and module spec S, such that

$M_{good} \models S$

$M_{bad} \not\models S$

$M_{fine} \models S$

We want to give formal meaning to

(*) Effect (*E*) can be caused
- **only** by external objects calling methods on internal objects, and
- **only** if the causing object has access to capability.

Assume that effect *E* invalidates assertion *A*.

Then, we could formalize **(*)** through

A ∧ “no external access to OCAP” is “invariant”

We need to determine

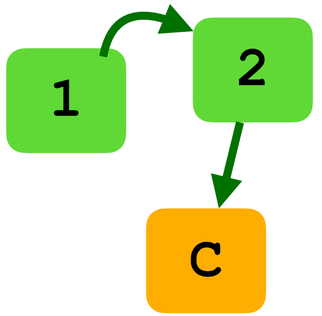
- “no external access to OCAP”
- “invariant”

We now determine

- “no external access to OCAP”
- “invariant”

1st Answer

- No external objects exist.



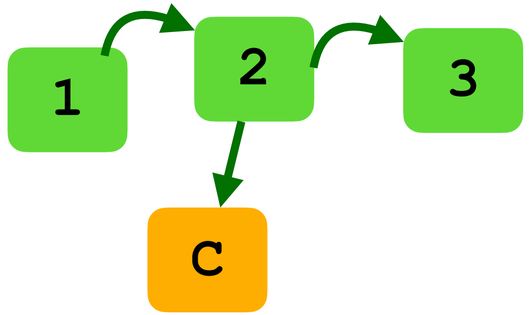
***Unsound*!**

We now determine

- “no external access to OCAP”
- “invariant”

2nd Answer

- No external objects exist.
- No external objects created.



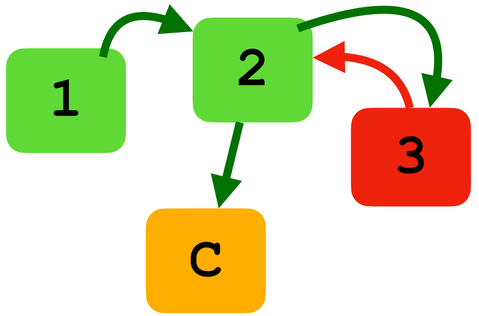
Too Strong!

We now determine

- “no external access to OCAP”
- “invariant”

3rd Answer

- No external object has direct access to OCAP



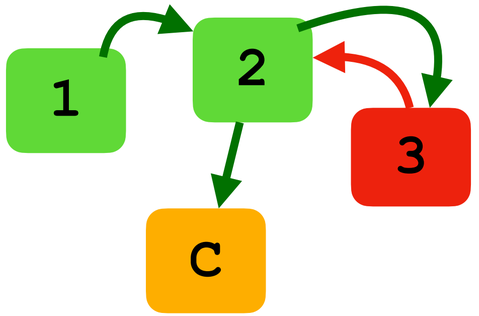
***Unsound*!**

We now determine

- “no external access to OCAP”
- “invariant”

4th Answer

- No external object has direct access to OCAP.
- No inrernal objects leak capability to OCAP.



Too strong!

We now determine

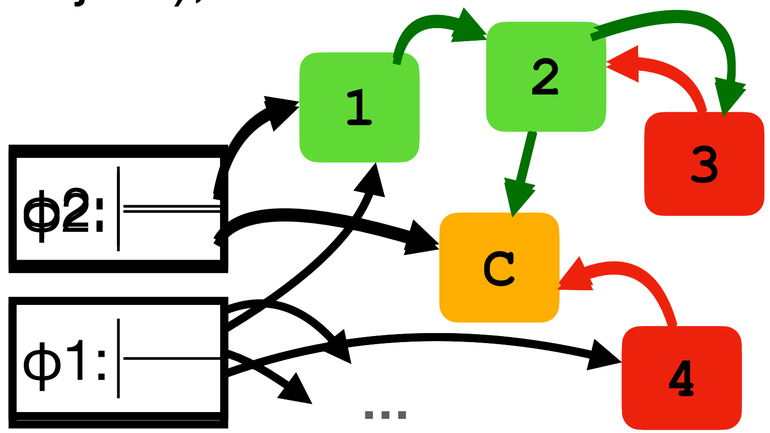
- “no external access to OCAP”
- “invariant”

5th Answer

- No *currently accessible* external object has direct access to OCAP.
- No internal objects leak access to OCAP.

invariant ≙ preserved in external states (`this` is external object),
during execution of current call

Our Approach!

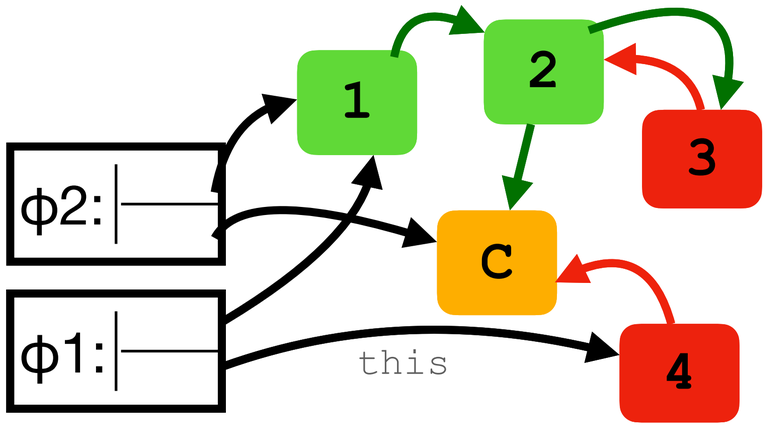


Remit_1_a : Express/Meaning of: No *currentlly accessible* external object has direct accees to o

Protection increases as we push frames

Def: o *protected*

$$\langle\!\langle o \rangle\!\rangle \triangleq \forall\, o'.[\ o' \text{ extl} \wedge o' \text{ reachble from top frame} \Rightarrow \forall f.[\ o''.f \neq o\ ]\ ]$$
$$\wedge\ [\ \texttt{this}\ \text{extl} \Rightarrow o \text{ not an arg}\ ]$$



$\Phi_1 \not\models \langle\!\langle C \rangle\!\rangle$
$\Phi_1 \not\models \langle\!\langle 2 \rangle\!\rangle$
$\Phi_1 \not\models \langle\!\langle 1 \rangle\!\rangle$

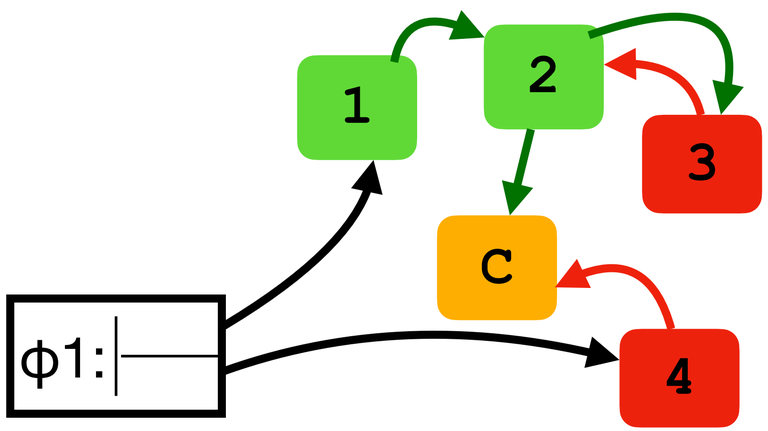
$\Phi_1\Phi_2 \models \langle\!\langle C \rangle\!\rangle$
$\Phi_1\Phi_2 \not\models \langle\!\langle 2 \rangle\!\rangle$
$\Phi_1\Phi_2 \models \langle\!\langle 1 \rangle\!\rangle$

Protection is “relative” to top frame

We also define …

Def: o *protected from* o'

$$\langle\!\langle o \rangle\!\rangle \not\leftarrow o' \quad \triangleq \quad \forall o''.[\ \ o'' \text{ extl} \wedge o'' \text{ reachble from } o' \ \Rightarrow \ \ \forall f.[\ o''.f \neq o\ ]\ \ ]$$



… $\models \langle\!\langle 2 \rangle\!\rangle \not\leftarrow 1$

… $\not\models \langle\!\langle 2 \rangle\!\rangle \not\leftarrow 3$

… $\models \langle\!\langle C \rangle\!\rangle \not\leftarrow 1$

… $\models \langle\!\langle C \rangle\!\rangle \not\leftarrow 3$

… $\not\models \langle\!\langle C \rangle\!\rangle \not\leftarrow 2$

Assertions may talk of protection and externals

$$A \quad ::= \quad e \mid e : C \mid \neg A \mid A \wedge A \mid \forall x : C.A \mid e : \texttt{extl} \mid \langle\!\langle e \rangle\!\rangle \nrightarrow e \mid \langle e \rangle$$

Remit_1_b : Express/meaning "invariant"

We propose "*scoped* invariants", of the form $\forall x_1{:}C_1,\ldots x_n{:}C_n\ \{\ A\ \}$

Eg $\forall$ `s:Shop.` { `s.account` $\neq$ `null` $\rightarrow$ « `s.account` key »

Any number of execution steps,
before returning from current frame

Definition

$$M \vDash \forall x_1{:}C_1,\ldots x_n{:}C_n\ \{\ A\ \} \triangleq \forall M'.\ \forall \sigma, \sigma'.\ \forall \alpha_1,\ldots\alpha_n.[$$

$$M, \sigma \vDash \texttt{this}\texttt{:}\ \text{ext} \wedge \alpha_1 :C_1,\ldots\alpha_n{:}Cn \wedge A[\alpha_1,\ldots\alpha_n / x_1,..x_n]$$

$$\wedge \quad M' \bullet M, \sigma \rightsquigarrow^* \sigma'$$

$$\wedge \quad M, \sigma' \vDash \texttt{this}\texttt{:}\ \text{ext}$$

$$\Rightarrow$$

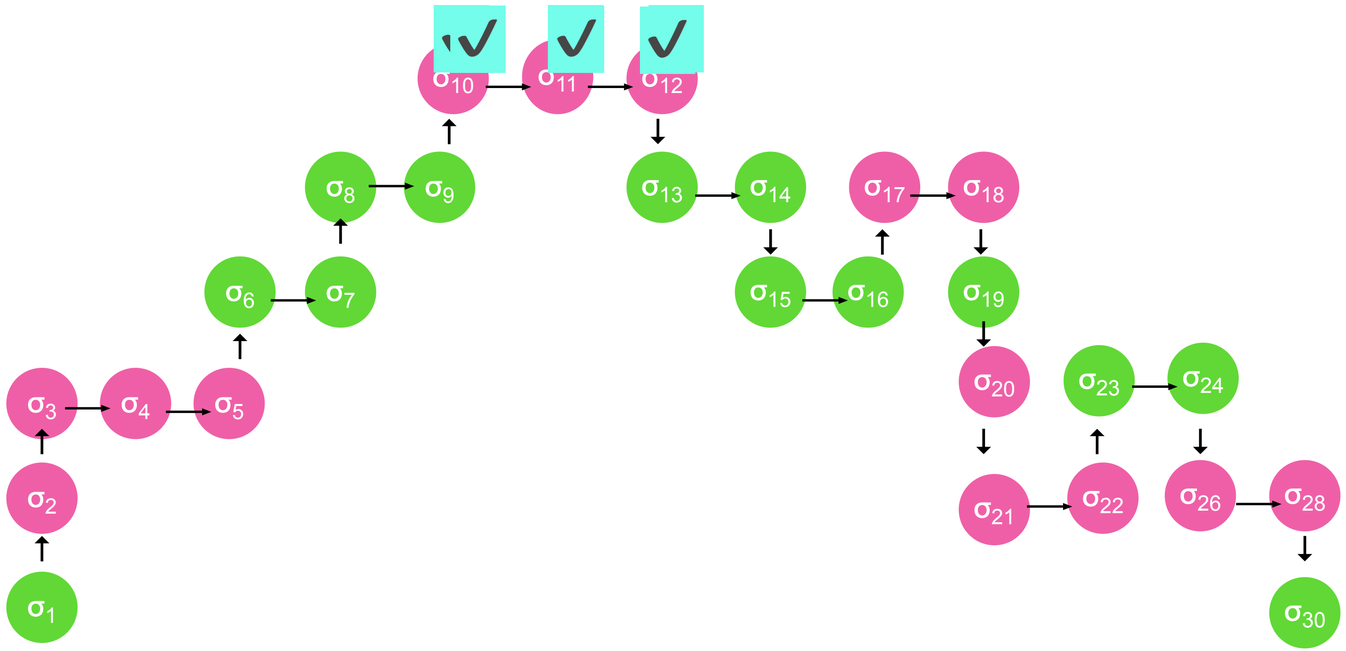
$$M, \sigma' \vDash A[\alpha_1,\ldots\alpha_n / x_1,..x_n]$$

$$]$$

An example:

Consider call graph below, with green disks for internal states (eg σ_2),
and pink disks for external states (eg σ_{28}).

$M \models \forall x{:}C.\ \{\ A\ \}$ means that $M, \sigma_{10} \models \alpha{:}C \wedge A[\alpha/x]$ implies $M, \sigma_{11} \models A[\alpha/x]$
$M, \sigma_{12} \models A[\alpha/x]$

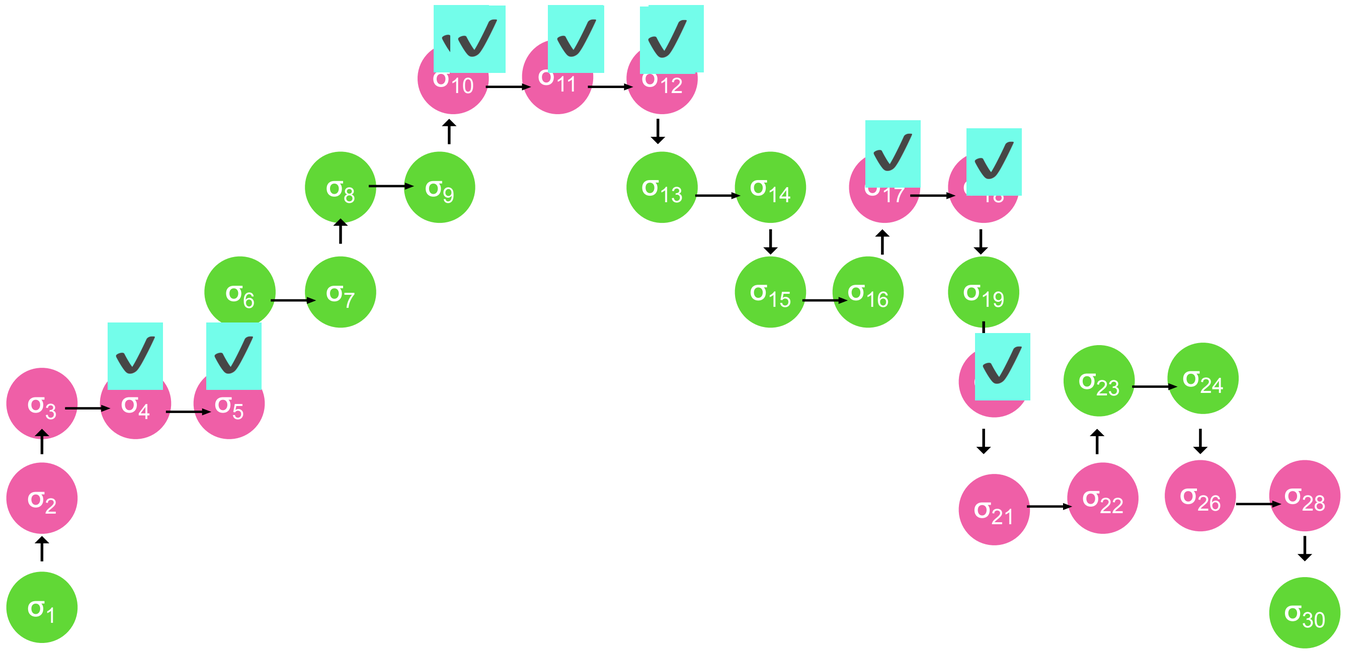


An example:

Consider call graph below, with green disks for internal states (eg σ_2),
and pink disks for external states (eg σ_{28}).

$M \models \forall x{:}C.\ \{\ A\ \}$ means that $M, \sigma_4 \models \alpha{:}C \wedge A[\alpha/x]$ implies

$M, \sigma_5 \models A[\alpha/x]$
$M, \sigma_6 \models A[\alpha/x]$
$M, \sigma_{10} \models A[\alpha/x]$
$M, \sigma_{10} \models A[\alpha/x]$
$M, \sigma_{11} \models A[\alpha/x]$
$M, \sigma_{17} \models A[\alpha/x]$
$M, \sigma_{18} \models A[\alpha/x]$
$M, \sigma_{20} \models A[\alpha/x]$



Challenge_1: A module spec S, such that

$M_{good} \models S$

$M_{bad} \not\models S$

$M_{fine} \models S$

API - agnostic:
a.blnce, a.key can be ghost

Talk about effects

Talk about emergent behaviour

S1 ≜ ∀ a:Account. { ⟪a⟫ }

S2 ≜ ∀ a:Account. { ⟪a.key ⟫ }

S4 ≜ ∀ a:Account, b:Num. { ⟪a.key ⟫ ∧ a.blnce ≥ b }

S5 ≜ { ⟪this.accnt.key ⟫ ↩ buyer ∧ this.accnt.blnce =b }
Shop::buy(buyer:external, item:Item)
{ this.accnt.blnce ≥ b }

$M_{bad} \not\models S2$

$M_{bad} \not\models S4$

$M_{bad} \not\models S1$

$M_{good} \models S2 \wedge S4 \wedge S5$

$M_{good} \not\models S1$

$M_{fine} \models S2 \wedge S4 \wedge S5$

$M_{fine} \not\models S1$

Remember Parity MultiSig Wallet Hack

Parity MultiSig Wallet Hack (150,000 ETH (~30M USD) 2017)

1) Attacker calls `initWallet(…)` and makes themselves the single owner
2) Attacker calls `execute(…)` and withdrawns all funds

An implementation that satisfies the below avoids the hack (assuming [illegible] is governed by the votes of the owners}

S10 ≜ ∀ msig:Multisig, o:Address.{ o ∈ msig.owner }

S11 ≜ ∀ msig:Multisig, o:Address { o ∈ msig.owner ∧ ⟪o⟫ }

S12 ≜ ∀ msig:Multisig, o:Address, v:Vote { o ∈ msig.owner ∧ ⟪o⟫ ∧ msig.

S13 ≜ ∀ msig:Multisig, o:Address, f:Funds

{ o ∈ msig.owner ∧ ⟪o⟫ ∧ msig.votes(o)=NO ∧ msig.funds = f }

The owner set only grows

No owner is leaked

Nobody can vote on behalf of others

No change of funds unless all owners agreed

Challenge_2: An inference system, such that

$$M_{good} \vdash S$$
$$M_{bad} \nvdash S$$
$$M_{fine} \vdash S$$

In the context of arbitrary, unlimited calls from internal to external,
and arbitrary, unlimited calls from external to internal.

Challenge_2: An inference system, such that …

Three Stages

Assume an underlying Hoare logic of triples with usual meaning $M \vdash_{ul} \{ A \}\, s \,\{ A' \}$

1st stage Expand it to Hoare logic of triples with usual meaning $M \vdash \{A\}\, s \,\{A'\}$

2nd Stage Expand triples to quadruples

$M \vdash \{A\}\, s \,\{A'\} \parallel \{A''\};$

Which promises that

- termination of s leads to a state satisfying A'
- intermediate external states satisfy A"

3rd Stage Rules for module satisfying a specification $M \vdash S$

Challenge_2: An inference system, such that …

1st stage

We extend some underlying Hoare logic to a Hoare logic of triples with usual meaning

$$\textsc{extend}\ \frac{M \vdash_{ul} \{ A \}\ s\ \{ A' \} \quad s \text{ contains no method call}}{M \vdash \{A\}\ s\ \{A'\}}$$

$$\textsc{types-1}\ \frac{s \text{ contains no method call}}{M \vdash \{x : C\}\ s\ \{x : C\}}$$

Challenge_2: An inference system, such that …

2nd stage

We expand triples to quadruples

INV

$$\frac{M \vdash \{A\}\, s\, \{A'\}}{M \vdash \{A\}\, s\, \{A'\} \parallel \{A''\}}$$

TYPES-2

$$\frac{M \vdash \{A\}\, s\, \{A'\} \parallel \{A''\}}{M \vdash \{x : C \wedge A\}\, s\, \{x : C \wedge A'\} \parallel \{A''\}}$$

COMBINE

$$\frac{M \vdash \{A_1\}\, s\, \{A_2\} \parallel \{A\} \qquad M \vdash \{A_3\}\, s\, \{A_4\} \parallel \{A\}}{M \vdash \{A_1 \wedge A_3\}\, s\, \{A_2 \wedge A_4\} \parallel \{A\}}$$

SEQU

$$\frac{M \vdash \{A_1\}\, s_1\, \{A_2\} \parallel \{A\} \qquad M \vdash \{A_2\}\, s_2\, \{A_3\} A}{M \vdash \{A_1\}\, s_1; s_2\, \{A_3\} \parallel \{A\}}$$

CONSEQU

$$\frac{M \vdash \{A_2\}\, s\, \{A_3\} \parallel \{A_4\} \qquad M \vdash A_1 \rightarrow A_2 \qquad M \vdash A_3 \rightarrow A_5 \qquad M \vdash A_4 \rightarrow A_6}{M \vdash \{A_2\}\, s\, \{A_5\} \parallel \{A_6\}}$$

Challenge_2: An inference system, such that …

2nd stage

We introduce triples for protection

$$\frac{u \overset{\text{txt}}{\neq} x}{M \vdash \{\, true \,\}\ u = \texttt{new}\ C\ \{\, \langle u \rangle \ \wedge \langle u \rangle \leftrightarrow\!\!\!\!\times\ x \,\}} \quad [\textsc{prot-new}]$$

$$\frac{M \vdash \{\, e = z \,\}\ stmt\ \{\, e = z \,\}}{M \vdash \{\ \langle e \rangle\ \}\ stmt\ \{\ \langle e \rangle\ \}} \quad [\textsc{prot-1}]$$

$stmt$ is free of method cals, or assignment to z

$$\frac{M \vdash \{\ z = e \wedge z' = e'\ \}\ stmt\{\ z = e \wedge z' = e'\ \}}{M \vdash \{\ \langle e \rangle \leftrightarrow\!\!\!\!\times\ e'\ \}\ stmt\ \{\ \langle e \rangle \leftrightarrow\!\!\!\!\times\ e'\ \}} \quad [\textsc{prot-2}]$$

$stmt$ is either $x := y$ or $x := y.f$, and $z, z' \overset{\text{txt}}{\neq} x$

$$\frac{x \overset{\text{txt}}{\neq} z}{M \vdash \{\ \langle y.f \rangle \leftrightarrow\!\!\!\!\times\ z\ \}\ x = y.f\ \{\ \langle x \rangle \leftrightarrow\!\!\!\!\times\ z\ \}} \quad [\textsc{prot-3}]$$

$$\frac{}{M \vdash \{\ \langle x \rangle \leftrightarrow\!\!\!\!\times\ z\ \wedge\ \langle x \rangle \leftrightarrow\!\!\!\!\times\ y'\ \}\ y.f = y'\ \{\ \langle x \rangle \leftrightarrow\!\!\!\!\times\ z\ \}} \quad [\textsc{prot-4}]$$

Challenge_2: An inference system, such that …

3rd stage

$$\frac{M \vdash \mathscr{S}pec(M)}{\vdash M}\ \textsc{WellFrm_Mod} \qquad \frac{M \vdash S_1 \qquad M \vdash S_2}{M \vdash S_1 \wedge S_2}\ \textsc{Comb_Spec}$$

Challenge_2: An inference system, such that …

3rd stage

$$\frac{???}{M \vdash \forall \overline{x : C}\{A\}}\ \textsc{invariant}$$

Challenge_2: An inference system, such that …

Protection is “relative” to a frame;
Our $-\!\!\triangledown$ operator

helps us switch to callee’s view

INVARIANT

$$\frac{M \vdash Encps(\overline{x : C} \wedge A) \quad \forall D, m : \texttt{mBody}(m, D, M) = \texttt{public}\ (\overline{y : D})\{\ stmt\ \} \implies M \vdash \{\ \texttt{this} : \texttt{D}, \overline{y : D},\ \overline{x : C} \wedge A \wedge A \text{-}\!\!\triangledown (\texttt{this}, \overline{y})\ \}\ stmt\ \{\ A \wedge A \text{-}\!\!\triangledown \texttt{res}\ \} \parallel \{\ A\ \}}{M \vdash \forall \overline{x : C}.\{A\}}$$

Remit_3: An inference system, such that we can prove external calls

Challenge_4: An inference system, such we can prove external calls

$$\frac{}{M \vdash \{\ y_0 : \texttt{ext} \quad , \quad ???\ \}\ u := y_0.m(y_1, ..y_n)\ \{\ ???\ \}\ \|\ \{\ ??\ \}}\ [\textsc{Call\_Ext}]$$

Challenge_4a: From Caller to Callee

We consider `Shop`'s method pay, and want to prove the external call, ie

$$\{\ \texttt{buyer:extl} \wedge \langle\!\langle \texttt{this.accnt.key} \rangle\!\rangle\!\!\nleftrightarrow \texttt{buyer} \wedge \texttt{this.accnt.blnce} = b\ \}$$

```
buyer.pay(this.accnt,price)
```

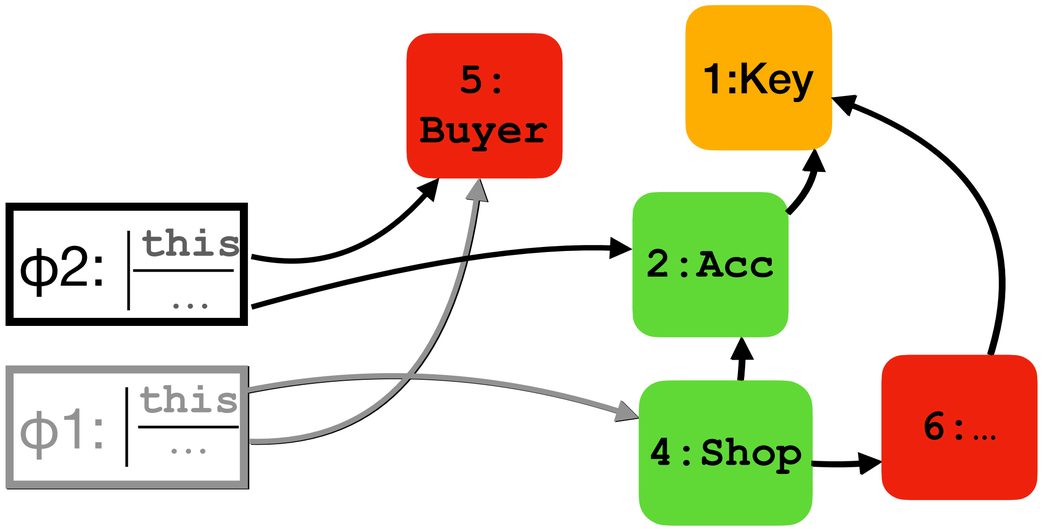
$\{\ \texttt{this.accnt.blnce} \geq b\ \}$ ...

We want to use S4, ie $\forall$ a:Account, b:Num. { ⟪a.key ⟫ ∧ a.blnce ≥ b }

BUT, $\phi_1 \not\models \langle\!\langle 1 \rangle\!\rangle$ 🤦

AHA!! to use S4, we only need ϕ_1,**callee** $\models \langle\!\langle 1 \rangle\!\rangle$ 😅

Indeed, $\phi_1\,\phi_2 \models \langle\!\langle 1 \rangle\!\rangle$ 😁



Therefore, we need an operator which mediates asserions between viewpoint of the callee and viewpoint of caller.

Challenge_4a: From Caller to Callee — The $-\triangledown$ operator

$\triangledown$ translates an assertion from the view of the callee to that of the caller.

Definition 6.1. [The $-\triangledown$ operator]

$$
\begin{array}{rcl}
\langle e \rangle -\triangledown \overline{y} & \triangleq & \langle e \rangle \leftrightarrow\!\!\!\!\times\, \overline{y} \\
(\langle e \rangle \leftrightarrow\!\!\!\!\times\, \overline{u}) -\triangledown \overline{y} & \triangleq & \langle e \rangle \leftrightarrow\!\!\!\!\times\, \overline{u} \\
(e : \texttt{extl}) -\triangledown \overline{y} & \triangleq & e : \texttt{extl} \\
e -\triangledown \overline{y} & \triangleq & e
\end{array}
\qquad
\begin{array}{rcl}
(A_1 \wedge A_2) -\triangledown \overline{y} & \triangleq & (A_1 -\triangledown \overline{y}) \wedge (A_2 -\triangledown \overline{y}) \\
(\forall x : C.A) -\triangledown \overline{y} & \triangleq & \forall x : C.(A -\triangledown \overline{y}) \\
(\neg A) -\triangledown \overline{y} & \triangleq & \neg (A -\triangledown \overline{y}) \\
(e : C) -\triangledown \overline{y} & \triangleq & e : C
\end{array}
$$

Example: ⟪this.accnt.key⟫ $-\triangledown$ buyer = ⟪this.accnt.key⟫ $+$ buyer

Lemma 6.2. For states σ, assertions A, so that $Stb^{+}(A)$ and $Fv(A) = \emptyset$, frame ϕ, variables $y_0, \overline{y}$:

$$
\begin{array}{lcl}
(2)\ M, \sigma \models A -\triangledown Rng(\phi) & \Longrightarrow & M, \sigma \triangledown \phi \models A \\
(3)\ M, \sigma \triangledown \phi \models A \wedge \texttt{extl} & \Longrightarrow & M, \sigma \models A -\triangledown Rng(\phi)
\end{array}
$$

Challenge_4a: From Caller to Callee — The $-\triangledown$ operator

$\triangledown$ translates

Protection is "relative" to a frame;

$\triangledown$ operator switches assertion to callee's viewpoint

$$(e : \texttt{extl})-\triangledown\overline{y} \triangleq e : \texttt{extl} \qquad (\neg A)-\triangledown\overline{y} \triangleq \neg(A-\triangledown\overline{y})$$
$$e-\triangledown\overline{y} \triangleq e \qquad (e : C)-\triangledown\overline{y} \triangleq e : C$$

Example: ⟪this.accnt.key⟫ $-\triangledown$ buyer = ⟪this.accnt.key⟫ $+$ buyer

Lemma 6.2. For states σ, assertions A, so that $Stb^{+}(A)$ and $Fv(A) = \emptyset$, frame ϕ, variables $y_0, \overline{y}$:

(2) $M, \sigma \models A-\triangledown Rng(\phi) \implies M, \sigma \triangledown \phi \models A$

(3) $M, \sigma \triangledown \phi \models A \wedge \texttt{extl} \implies M, \sigma \models A-\triangledown Rng(\phi)$

Challenge_4: An inference system, such we can prove external calls

$$\frac{}{M \vdash \{\ y_0 : \texttt{ext} \quad ,\quad \} \ u := y_0.m(y_1, ..y_n)\ \{\ ???\ \}\ \|\ \{\ ??\ \}}\ [\textsc{Call\_Ext}]$$

Challenge_4: An inference system, such we can prove external calls

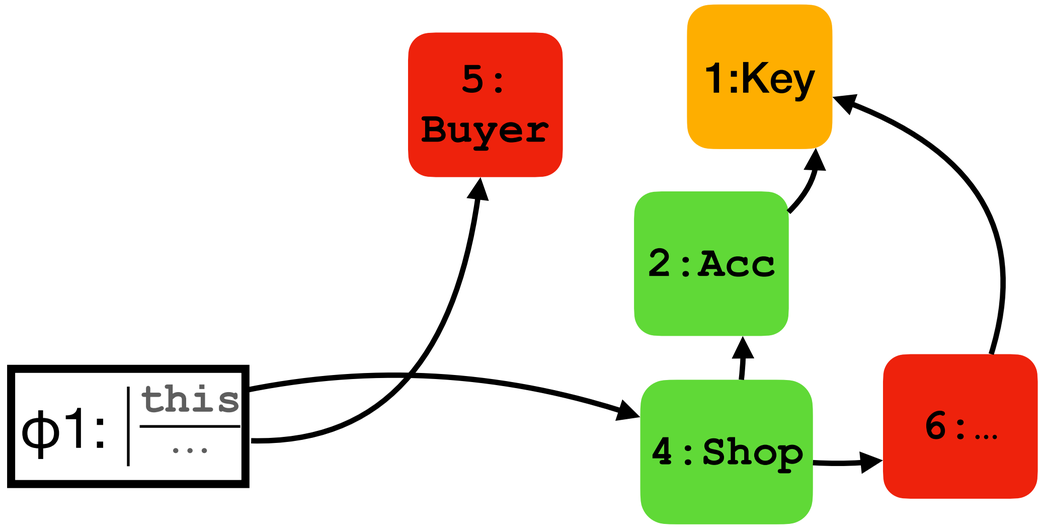
$$\frac{\vdash \; M \; : \; \forall \overline{x : D}\{A\}}{M \vdash \{ \; y_0 : \texttt{ext} \wedge \overline{x : D} \wedge A \multimap \forall \overline{y} \; \} \, u := y_0.m(y_1, ..y_n) \, \{ \; A \multimap \forall \overline{y} \; \} \; \| \; \{ \; A \; \}} \; [\textsc{Call\_Ext}]$$

Using [Call_Ext] we can, indeed, prove

$$\{\ \mathtt{buyer}:\mathtt{extl} \wedge \langle\!\langle \mathtt{this.accnt.key} \rangle\!\rangle \leftrightarrow \mathtt{buyer} \wedge \mathtt{this.accnt.blnce} = b\ \}$$

$$\mathtt{buyer.pay(this.accnt,price)}$$

$$\{\ \mathtt{this.accnt.blnce} \geq b\ \} \ldots$$



Using our quadruples, we have proven

$$M_{good} \vdash S2 \wedge S4 \wedge S5$$

$$M_{fine} \vdash S2 \wedge S4 \wedge S5$$

Moreover, we have proven

$$\vdash M \wedge M \vdash \{A\}\ stmt\ \{A'\} \,||\, \{A''\} \Rightarrow M \models \{A\}\ stmt\ \{A'\} \,||\, \{A''\}$$

$$\vdash M \Rightarrow M \models S$$

Summary

- Distinction between external/internal objects
- ⟪e ⟫: expresses that e is protected from reachable external objects
- Specifications talk about necessary conditions for effect:

  ∀ x: … { ⟪e ⟫ ∧ A }

  means that A is preserved as long as **capability** e is ptotected
- API-agrnositc spec,
- “Algorithmic” inference system system,
- Reason with open calls
- Protaction, ⟪e ⟫ relative to frame. Use —▽ to switch view

Surprises

- Frame-related concepts
  - Protected object
  - Scoped Invarinats
  - ▽ to switch view to callee frame
- Started with *necessary conditions*,
  but ended up using *sufficient conditions* to reason about them
- Started with temporal logics,
  but ended up using invariants
- Hoare logic extensions
- Invariants — twenty years later …

A Unified Framework for Verification Techniques for Object Invariants

S. Drossopoulou[1], A. Francalanza[2], P. Müller[3], and A. J. Summers[1]

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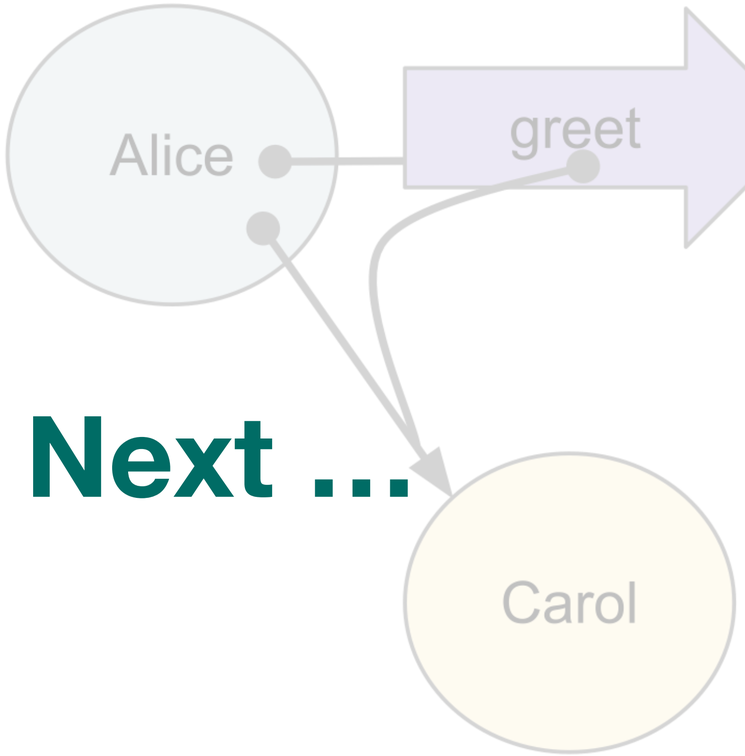
[3] Microsoft Research, Redmond

Abstract. Object invariants define the consistency of objects. They have subtle semantics because of call-backs, multi-object invariants and subclassing. Several visible-state verification techniques for object in-



Next …

- Modules
- Mechanize proofs
- Completeness?
- Revisit protection:
  - What if more than one capability for an effect?
  - Ownership types, membranes etc?
  - Instance-level protection?
  - assertions rather than objects to protect
- Other programming Paradigms (Ethereum, ECMAscript)
- Better interaction with underlying Hoare logics
- Tool

Thank You!

by the end of next week