Squashing Bugs and Empowering Programmers with User-Centered Programming Language Design

MICHAEL COBLENZ

BUT FIRST: FEEDBACK

IT'S TOO HARD TO WRITE SAFE SOFTWARE

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FTC warns companies to remediate Log4j security vulnerability

By: This blog is a collaboration between CTO and DP
2022 9:19AM

22 September 2021

Integer Overflow resulting in OOB Access in CoreGraphics as used by iMessage (ForcedEntry)

#Binary

Original Post:
ero-Click iPhone Exploit

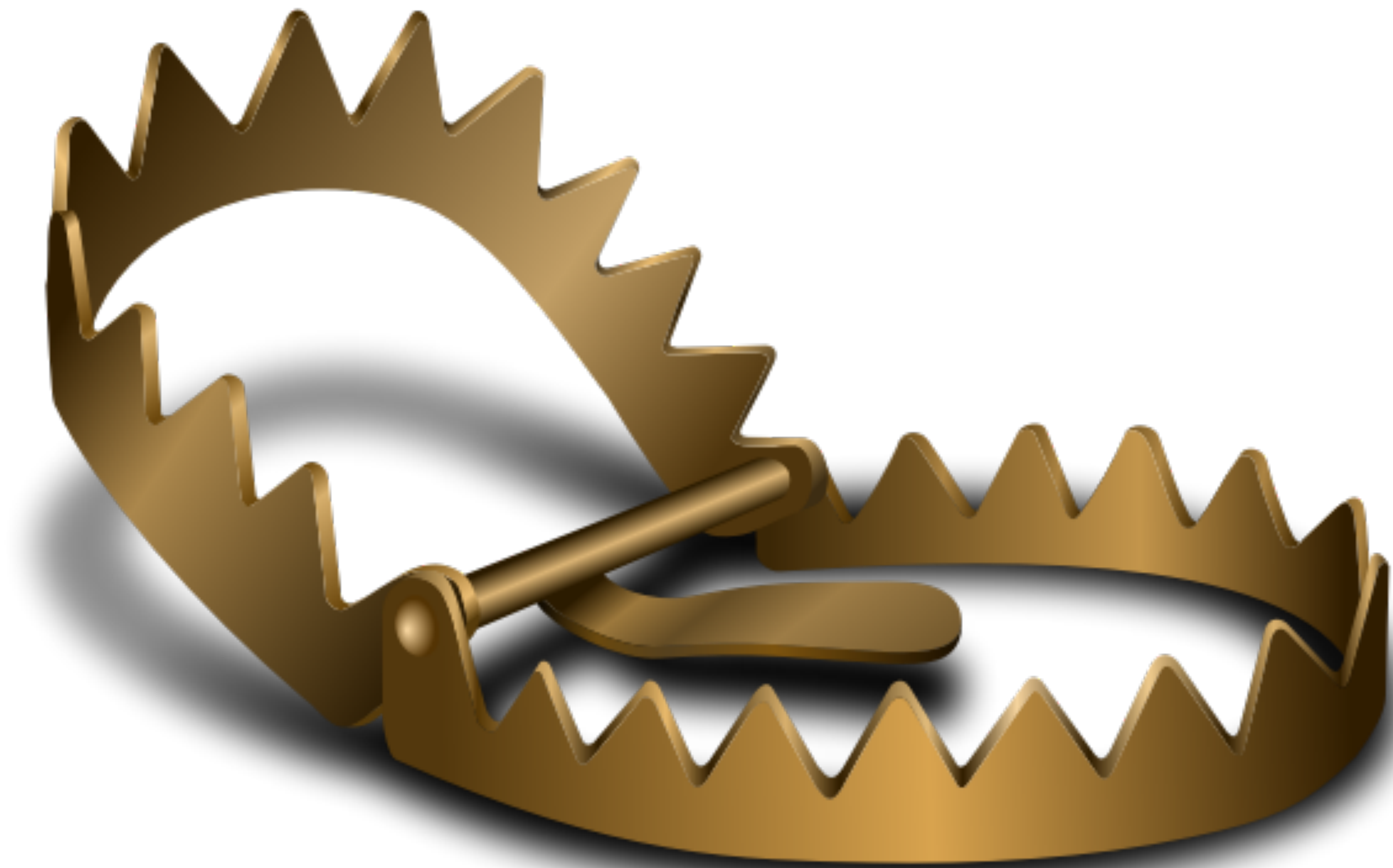
TECH • AMAZON

Amazon says software problem was at root of huge Internet outage this week

BY **SPENCER SOPER**, **JACK GILLUM**, AND **BLOOMBERG**
December 10, 2021 8:04 PM EST

…"Basically, a bad piece of code was executed automatically and it caused a snowball effect," Forrester analyst Brent Ellis said.

PROGRAMMING LANGUAGES LAY TRAPS



TRAPS PROGRAMMING LANGUAGES LAY

- In an object-oriented language: call `foo() on x.`
  - Not if `x`'s type doesn't implement `foo()`
  - Not if `x` is `null`
  - Not if `x` is a reference to freed memory
- Call `person.setAddress(a)`?
  - Is `person` used as a key in a hash table?

NO FREE LUNCH

- Goal: make serious errors less common
  - e.g. security
- Also want to keep the cost low
- Let's talk about an everyday safety problem…

Option A

- Easy to dispense
- Easy to replace roll
- …oops, the roll fell off.

https://www.hansgrohe-usa.com/articledetail-logis-toilet-paper-holder-40526000

Option B

- Can't steal rolls or paper
- Replacing roll is a privileged operation
- VERY ANNOYING to dispense

https://accessories.toiletpartitions.com/product/bradley-5402-dual-roll-toilet-paper-dispenser/

IMPROVING PRODUCTIVITY THROUGH USABILITY

- My goal: enable designers to create safer programming languages with *reasonable, known* user costs
  - Choose *relevant* guarantees
  - Minimize user cost to obtain those guarantees
- Evaluate with users; provide evidence of:
  - Fewer bugs
  - Less time
  - More likely to complete task correctly within time window
  - Less training required

PLIERS: PROGRAMMING LANGUAGE ITERATIVE EVALUATION AND REFINEMENT SYSTEM

- A systematic method for making languages effective for programmers
    - while retaining key safety properties
- Mantra of HCI: **the user is not like me**
    - (similar to the *expert blind spot* in teaching)
- Involve **users** throughout design process
- Soon, I'll show how I leveraged PLIERS in specific designs
- Five steps

PLIERS: PROGRAMMING LANGUAGE ITERATIVE EVALUATION AND REFINEMENT SYSTEM

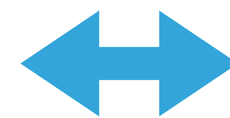
Need-finding

- Interviews
- Corpus studies
- Contextual inquiry

Conception

Formal:

- Core calculus
- Identify properties
- Proof sketches



User-Centered:

- Example programs
- Interpreter/compiler
- Natural programming elicitation

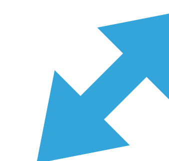
Risk Analysis

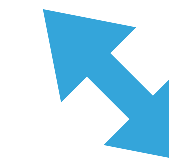
- Cognitive Dimensions of Notations
- Comparison with prior systems
- User research

Refinement

Evaluation:

- Usability studies
- Natural programming
- Performance testing
- Case studies





Theory:

- Core calculus
- Proofs of key properties

Prototype:

- Interpreter/compiler
- Programmer experience

Assessment

- Usability studies
- Randomized controlled trials (RCT)

TODAY

- **Obsidian:** a safer smart contract language [TOPLAS20, OOPSLA20, TOCHI21]

OBSIDIAN

https://en.wikipedia.org/wiki/File:Lipari-Obsidienne_(5).jpg

SMART CONTRACT SECURITY

- Blockchains: for users who do not trust each other
  - High-stakes applications ("smart contracts"). Hard to fix deployed bugs.
- Bugs: > $80 million stolen
  - via programming traps laid by Solidity
- Programming is hard. How can we design languages that are less error-prone?

[1] https://paritytech.io/the-multi-sig-hack-a-postmortem/

RIGOROUS DESIGN PROCESS

- *Need-finding:* studied domain
- *Conception:* identified safety properties, technical approach
- *Risk analysis*: relative to prior languages
- *Refinement*: language design, formal model, case studies
  - a *historical tour*
- *Assessment:* formal proof, RCT comparing Obsidian to Solidity

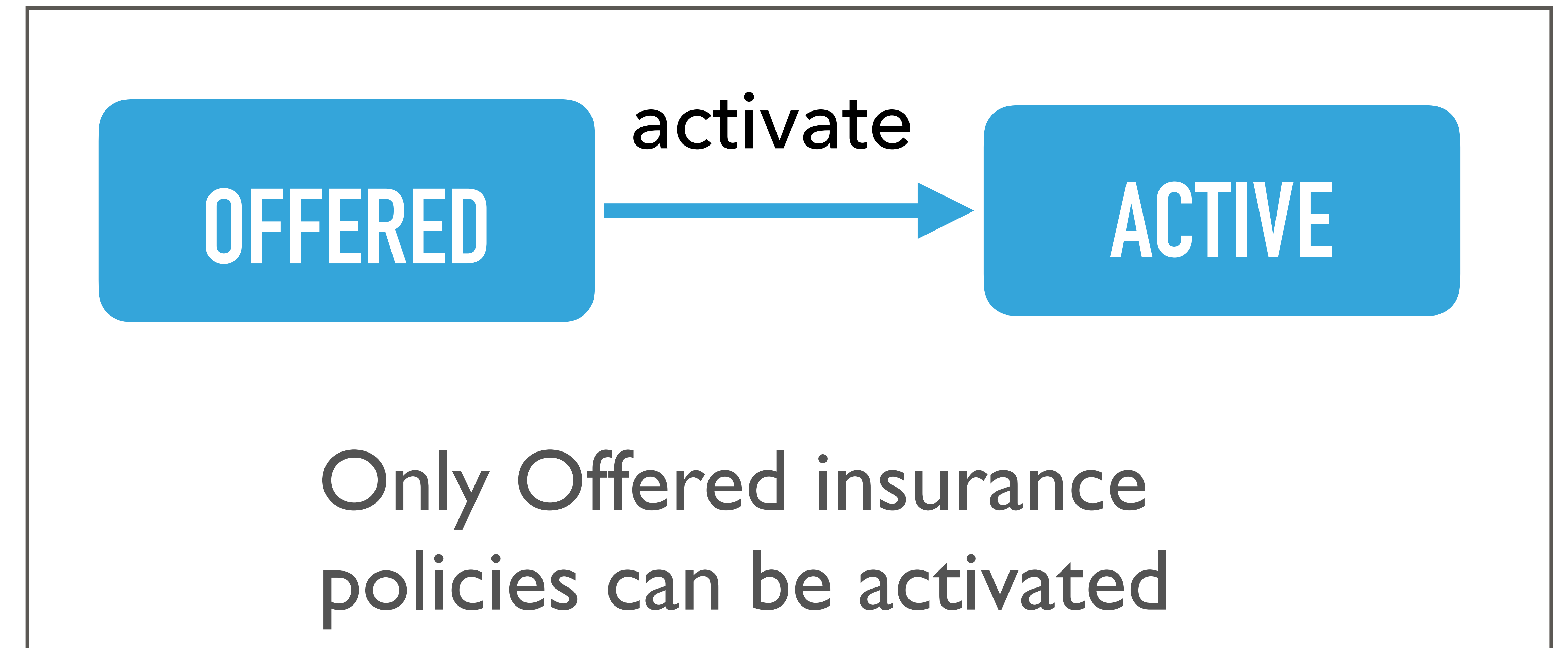
NEED FINDING AND CONCEPTION

- Blockchain applications frequently:
  - Manage important *assets*, such as virtual currencies
    - Some smart contract bugs have involved trapped/forgotten assets [Delmolino et al. 2015]
  - Support different operations depending on state
    - DAO hack exploited re-entrancy – invocation when contract is in an inconsistent state
  - Combining assets with typestate is new, and user studies had not evaluated the usability of typestate or assets

Linearity
[Wadler 1990, Girard 1987]

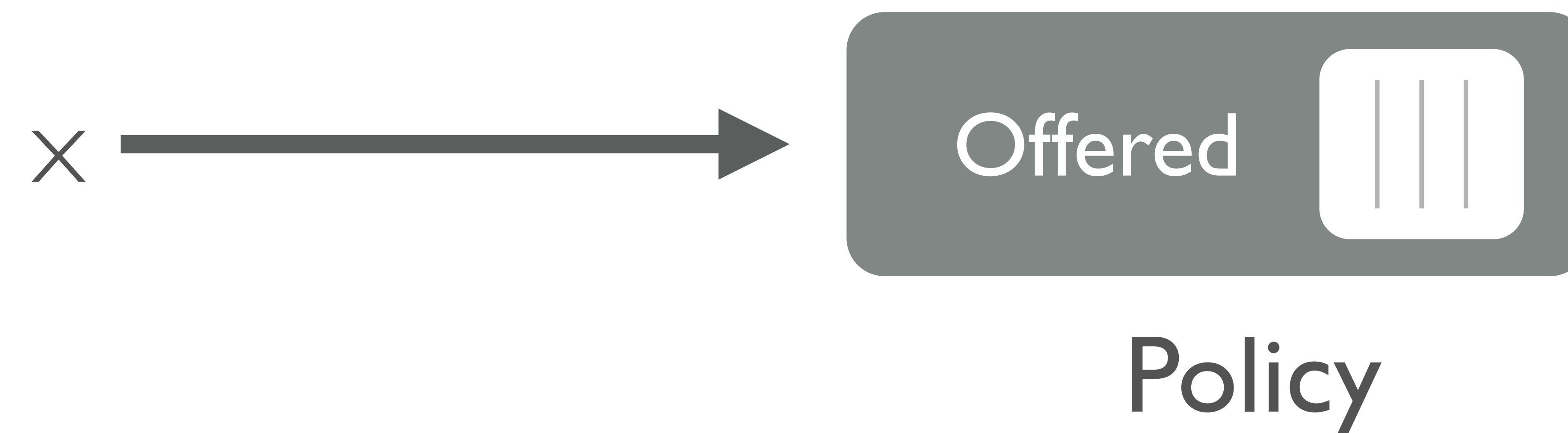
Typestate
[DeLine 2004]

WITHOUT TYPESTATE (e.g., JAVA)

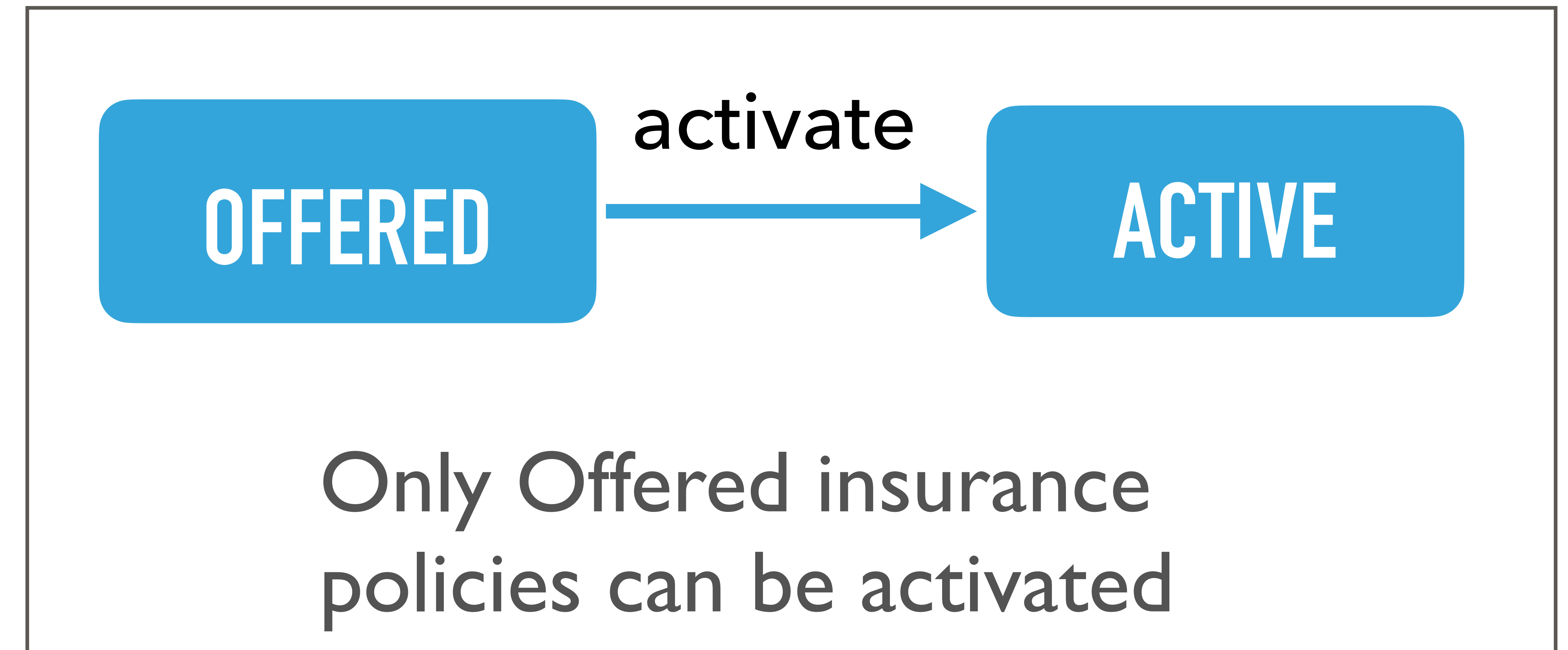


- Type *lacks* state information

```
buy(Policy x) {
  x.activate();
}
```

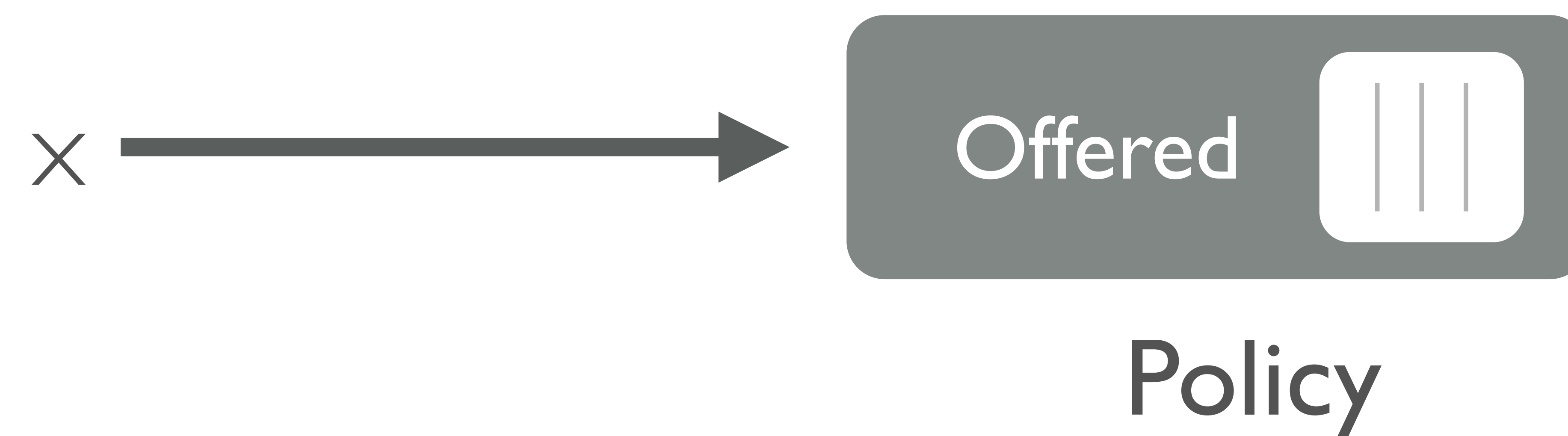


WITH TYPESTATE (OBSIDIAN)



- Type *includes* state information

```
buy(Policy@Offered x) {
  x.activate();
}
```



WITHOUT ASSETS (e.g., JAVA)

```
spend(Token t) {
    transferToken(t, alice);
    transferToken(t, bob);
}
transferToken(Token t, Person p) {
    …
}
```

Compiler says OK!

WITHOUT ASSETS (e.g., JAVA)

```
spend(Token t) {
    transferToken(t, alice);
    transferToken(t, bob);
}
```

Compiler says OK!

Opportunity: references can encode TWO kinds of information:

- Information about referenced object (Token)
- Information about the *relationship* with the referenced object

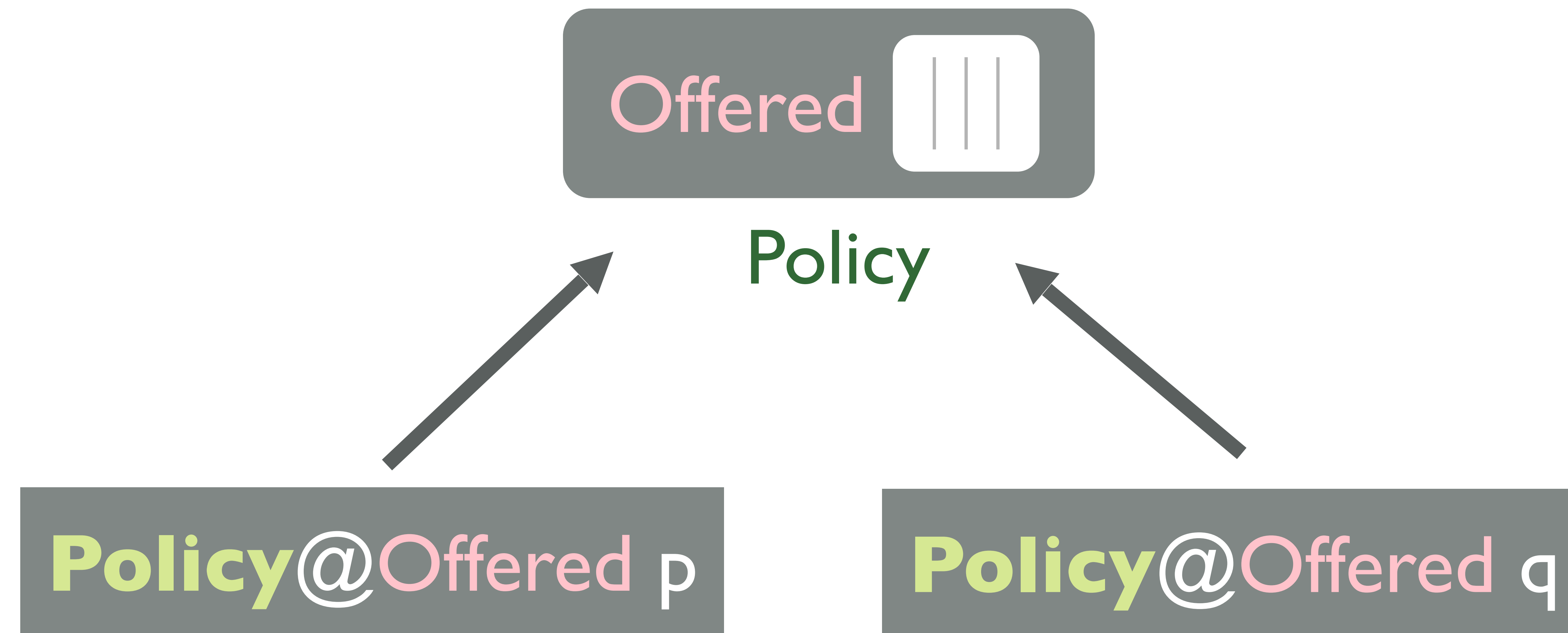
WITH ASSETS (OBSIDIAN)

```
spend(Token@Owned >> Unowned t) {
    transferToken(t, alice);
    transferToken(t, bob);
}

transferToken(Token@Owned >> Unowned t) {
    …
}
```

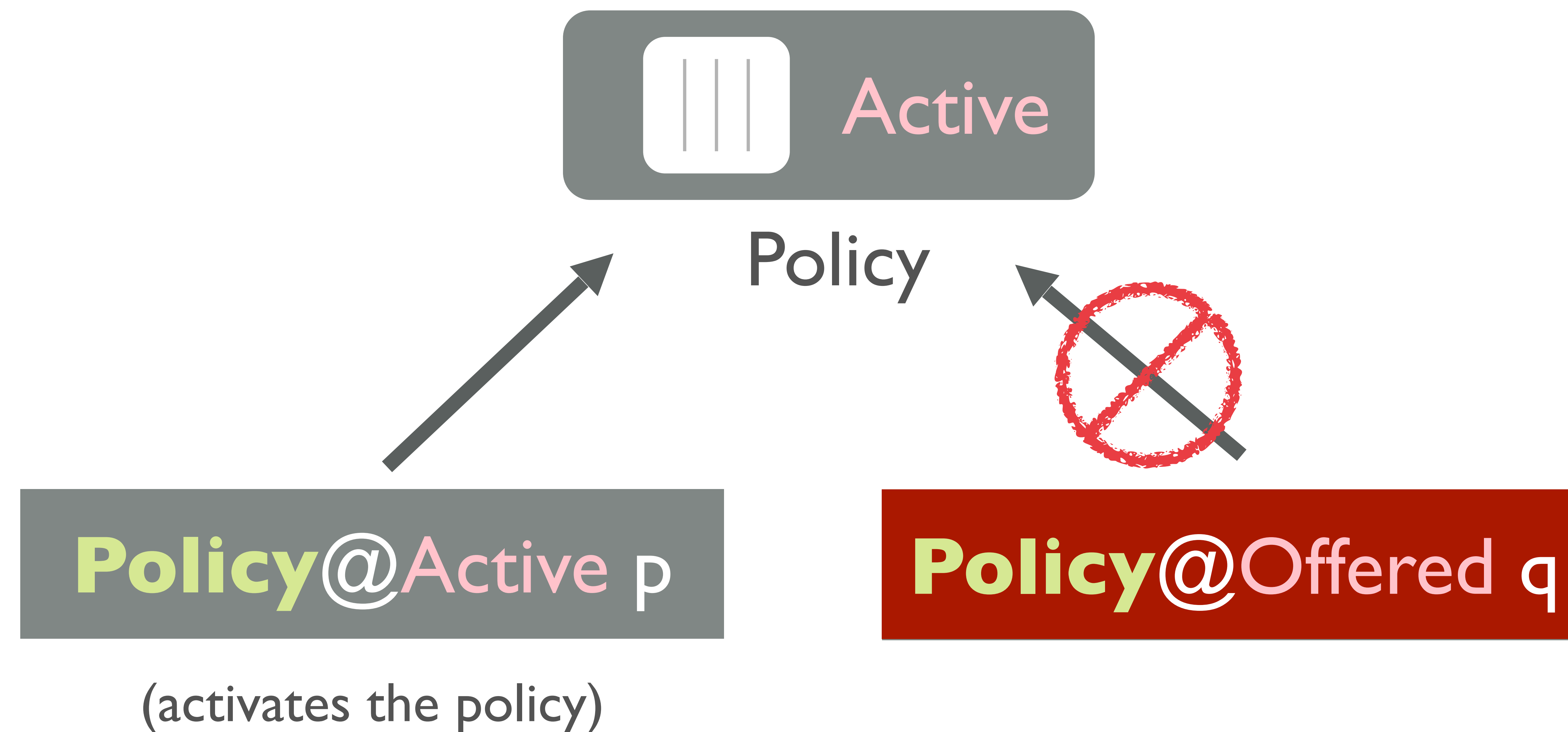
Compiler says ERROR!

TECHNICAL CHALLENGE: TYPESTATE AND ALIASING



Two fields think they know what state the policy is in…

TECHNICAL CHALLENGE: TYPESTATE AND ALIASING



If there is a typestate-specifying reference, then no other reference can change typestate.

OBSIDIAN BY EXAMPLE: PARAMETRIC INSURANCE

- Real client: World Bank
- Automated insurance policies via blockchain
  - Great in countries without trusted insurance companies
- Insure crops against *July rain < 2 in.*
- Insurance pays out if weather meets criteria

OBSIDIAN

```
contract Policy {
  state Offered {
    int cost;
    int expirationTime;
  }

  state Active;
  state Expired;


  Policy@Offered(int c, int expiration) {
    ->Offered(cost = c, expirationTime = expiration);
  }

  transaction activate(Policy@Offered >> Active this) {
    ->Active;
  }
```

cost, expirationTime always in scope; must be repeatedly reinitialized

Obsidian is shorter overall

SOLIDITY

```
contract Policy {
  enum States {Offered, Active, Expired}
  States public currentState;
  uint public cost;
  uint public expirationTime;

  constructor (uint _cost, uint _expirationTime) public {
    cost = _cost;
    expirationTime = _expirationTime;
    currentState = States.Offered;
  }

  function activate() public {
    require(currentState == States.Offered,
        "Can't␣activate␣Policy␣not␣in␣Offered␣state.");
    currentState = States.Active;
    cost = 0;
    expirationTime = 0;
  }
```

Explicit, verbose state checks (easy to omit)

ITERATING ON THE DESIGN

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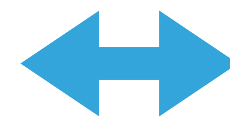

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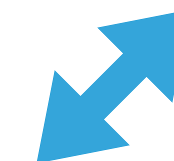

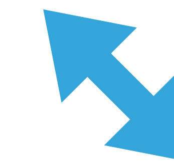

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FORMATIVE STUDY

- How can we evaluate the design proposal without implementing the whole language?

WIZARD OF OZ

- Traditional Wizard of Oz: experimenter remote-controls a prototype (to avoid implementing the “real” system)
- Users had a text editor; an experimenter simulated error messages

MOCK ENVIRONMENTS

- Goal: avoid teaching participants a whole new language
  - Teaching is high-cost
  - Effects of independent variable are conflated with other effects of new language
- Approach: back-port language changes to a familiar language

INITIAL PLAN (BASED ON PRIOR WORK)

- Example Annotation: **`owned`** `Bond@Sold`

  Permission Typestate

- Benefit: orthogonal permission and typestate specifications

ORTHOGONAL OWNERSHIP AND TYPESTATE (PRESENTED IN JAVA)

```
@Owned Prescription.FULL
```

- Lab study (Java annotations)
  - Asked participants to fix a typestate- and ownership-related bug
  - Allowing duplicate prescription refills
- Result: users had serious difficulties
  - "I haven't seen…types that complex in an actual language…enforced at compile time."
  - Participants thought about ownership *dynamically*, not statically
  - Expanded tutorial and practice did not seem to help
- Reflected a collection of different problems

ASSIGNMENT AND PARAMETER-PASSING

- Initial design: @Owned means acquires ownership

```
transaction deposit (Token@Owned t) {
  …
}
```

- User study results (N=6): this is confusing
  - *"when I [annotate this constructor type* **@Owned***], I'm not sure if I'm making a variable owned or I'm transferring ownership."*

- Revised design: make change in ownership explicit

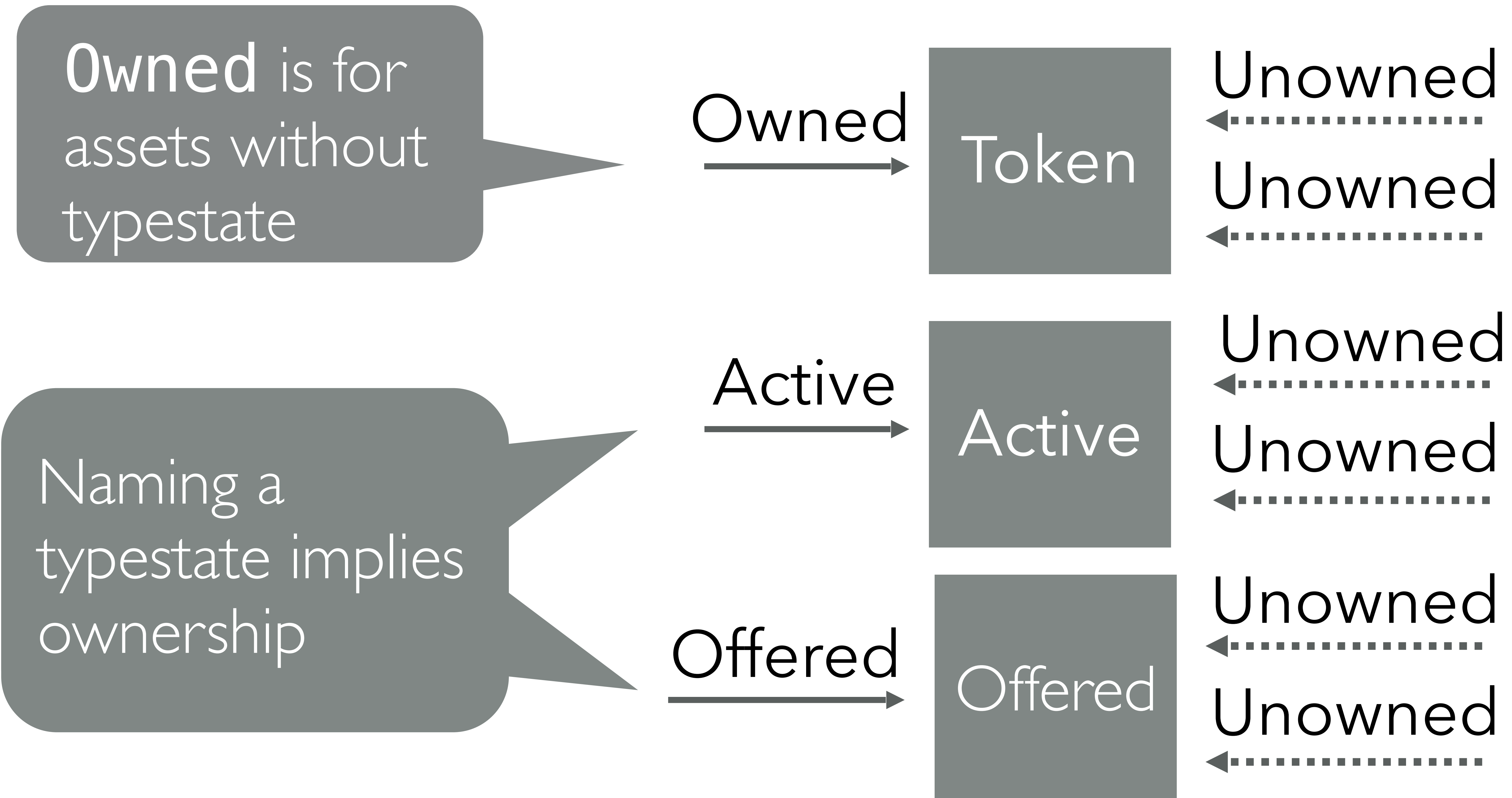
```
transaction deposit (Token@Owned >> Unowned t) {
  …
}
```

TYPE DECLARATIONS

- Initial design (from prior work): always specify typestate when declaring variable
- User study results (N=5): Too confusing!
  - ```
    Policy@Offered p = new Policy();
    p.activate();
    ```
- Revised design
  - Specify initial typestate, and any transition, in method signature (modularity)
  - No typestate on variables; support static typestate assertions

```
[s1 @ Offered];
```
```

REVISED DESIGN COMBINES TYPESTATE AND OWNERSHIP



~~`owned Policy@Offered`~~

Example types:

- `Token@Owned`
- `Policy@Offered`

- Simplifies design
- Avoids reasoning about ownership separate from typestate
- Aligns notation with abstraction

SILICA: A SOLID FOUNDATION FOR OBSIDIAN

Expression typing

$$\Gamma; \Delta \dashv e : T \vdash \Delta'$$

Splitting permissions

$$T_1 \Rrightarrow T_2 / T_3$$

Evaluation

$$\Sigma, e \rightarrow \Sigma', e'$$

Theorems proved

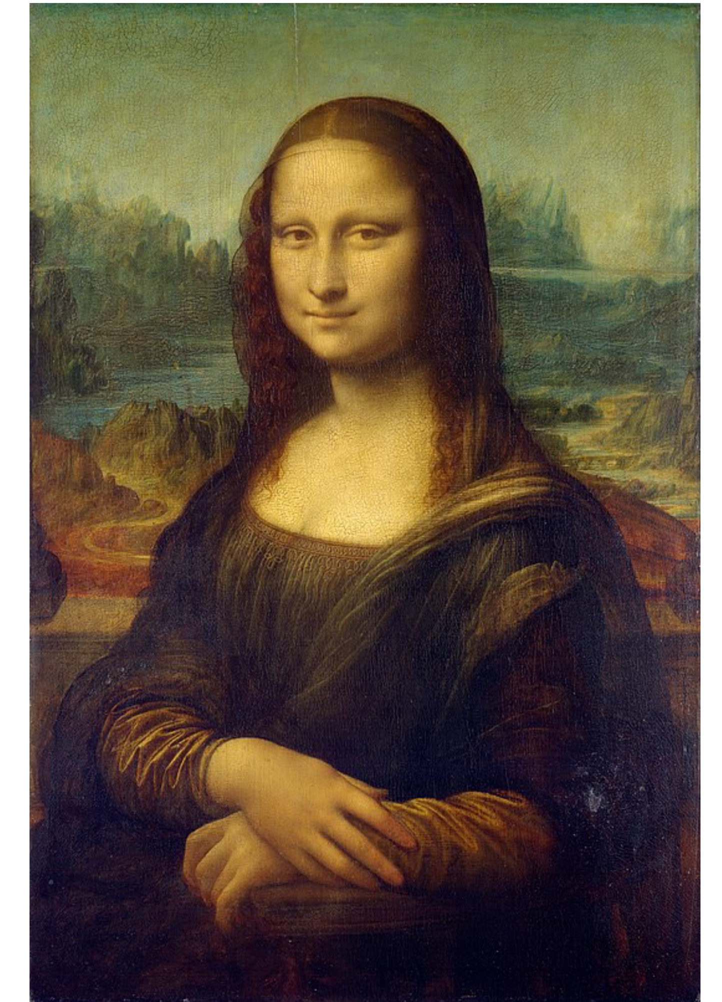
- Progress
- Preservation
- Asset retention

RANDOMIZED CONTROLLED TRIAL

- Is Obsidian *better* than Solidity?
- Recruited 20 Java programmers
- Tutorial: about 90 minutes

AUCTION

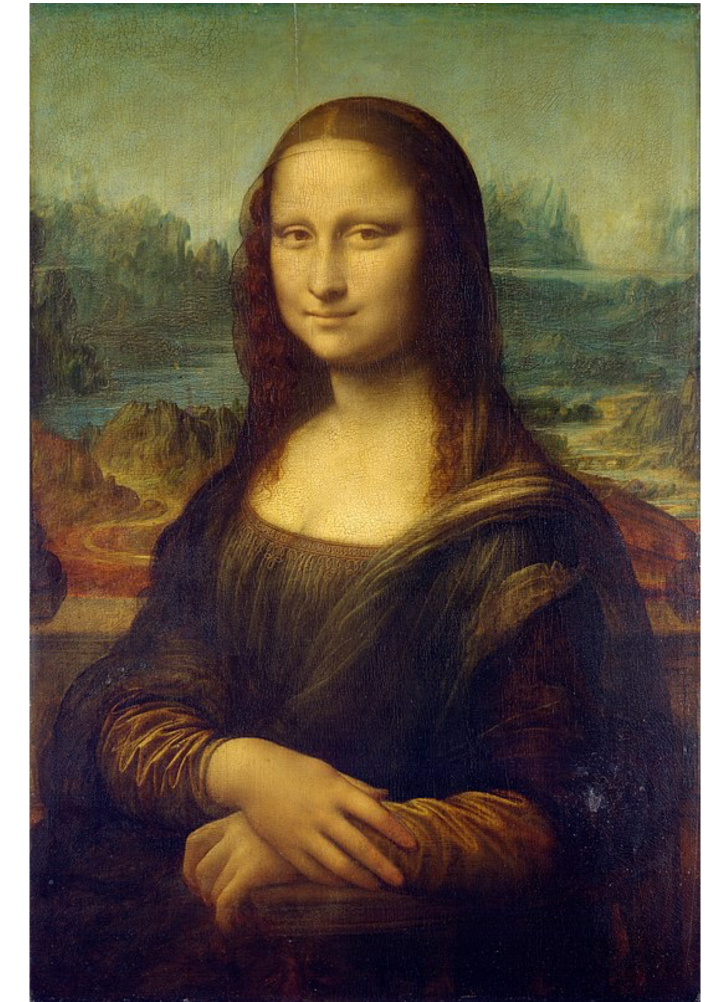
Escrow



An item to be auctioned

AUCTION

Escrow



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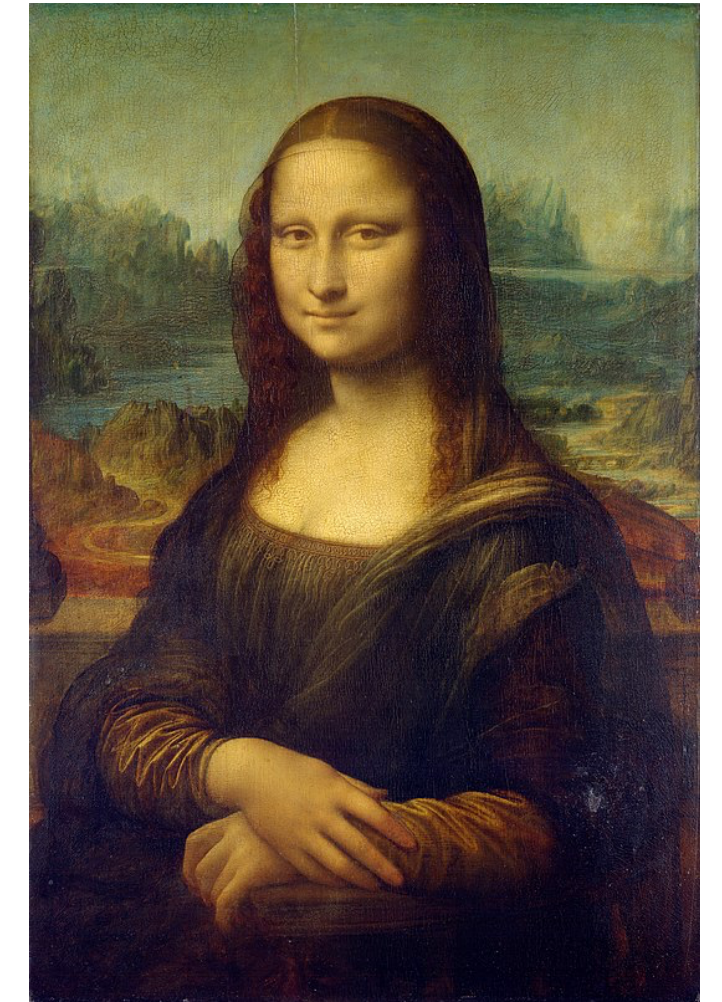

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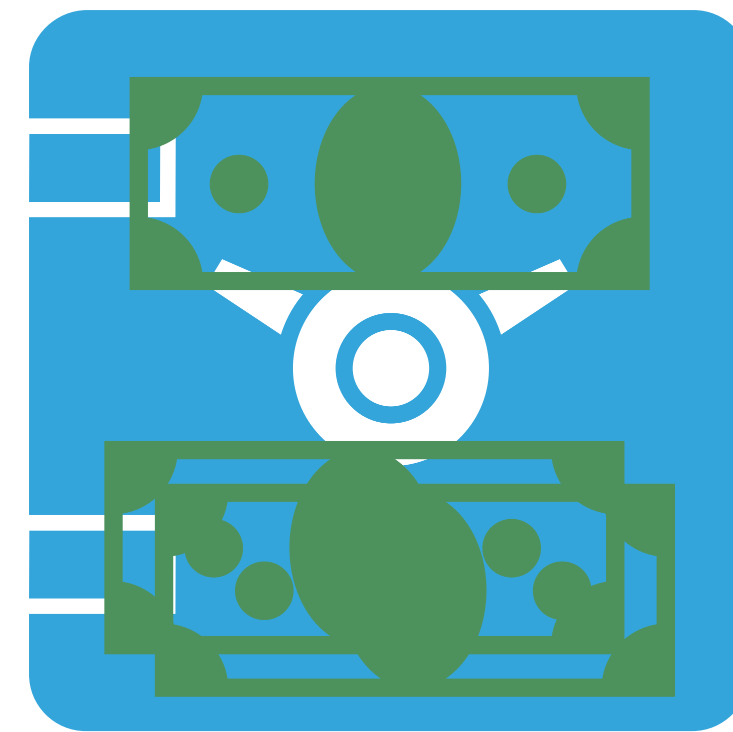
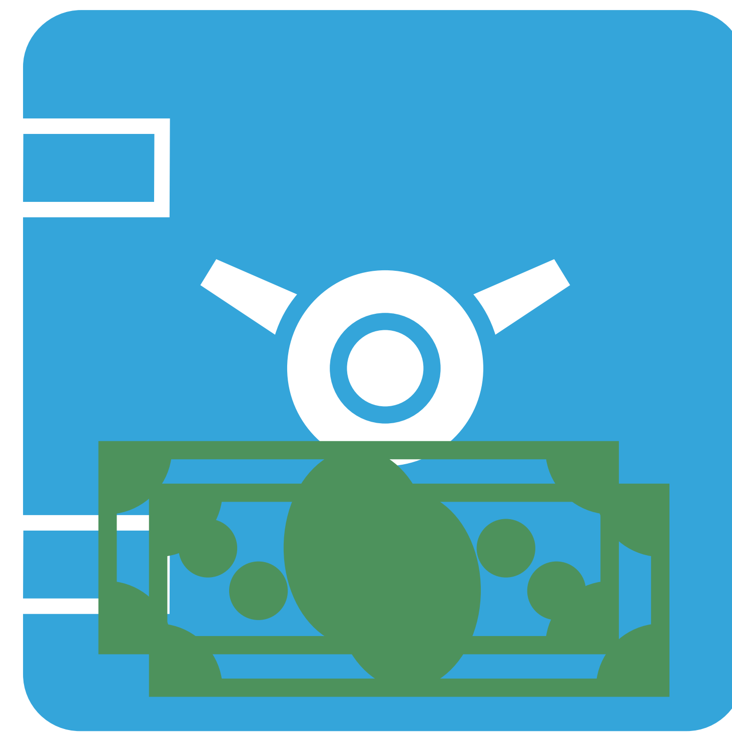
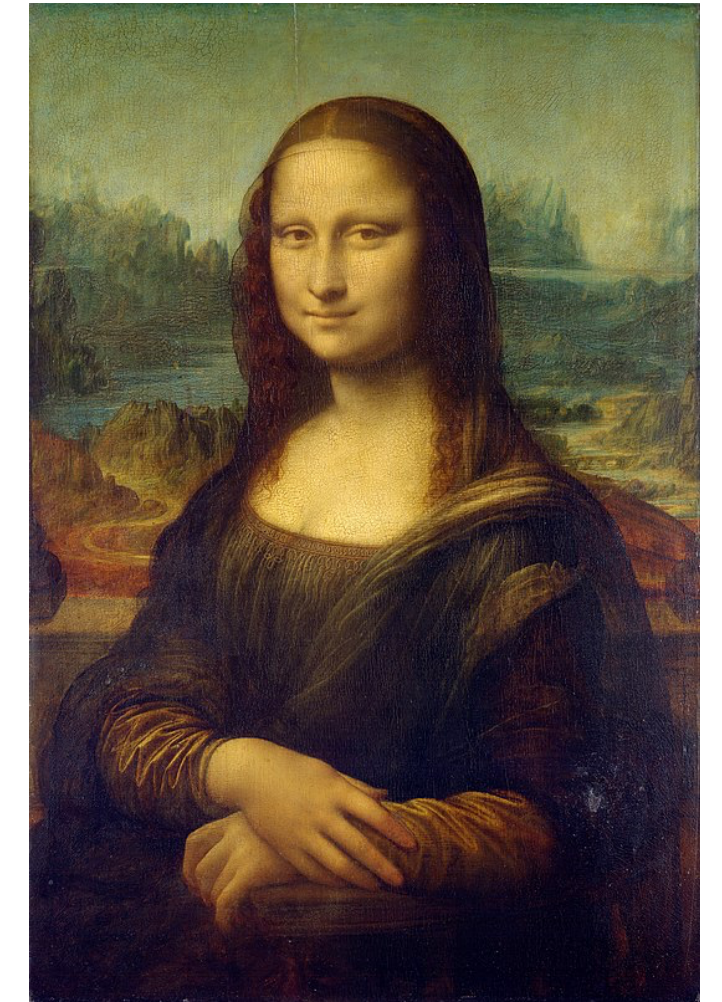


Escrow

AUCTION



Escrow



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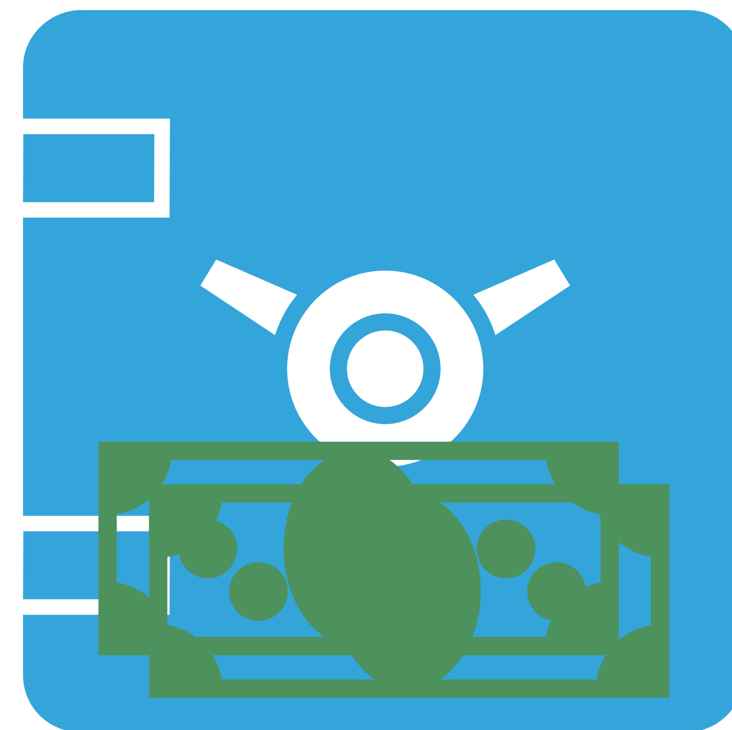

Escrow

AUCTION TASK

Condition: Solidity
Time limit: 30 minutes

```
contract Auction {
    address maxBidder; // the bidder who made the highest bid so far
    uint maxBidAmount;
    // 'payable' indicates that we can transfer money to this address
    address payable seller;

    // Allow withdrawing previous bid money for bids that were outbid
    mapping(address => uint) pendingReturns;

    enum State { Open, BidsMade, Closed }
    State state;

    constructor(address payable s) public {
        seller = s;
        state = State.Open;
    }
    …
```

implements *withdrawal pattern*

```
function bid() public payable {
       if (state == State.Open) {
           maxBidder = msg.sender;
           maxBidAmount = msg.value;
           state = State.BidsMade;
       }
       else {
           if (state == State.BidsMade) {
               //if the newBid is > than the current Bid
               if (msg.value > maxBidAmount) {
                   //1. TODO: fill this in.


               }
               else {
                   //2. TODO: return the newBid money to the bidder,
                   //   since the newBid wasn't high enough.
                   //   You may call any other functions as needed.

              }
           }
           else {
               revert ("Can only make a bid on an open auction.");
           }
       }
   }
```

```
function bid() public payable {
        if (state == State.Open) {
            maxBidder = msg.sender;
            maxBidAmount = msg.value;
            state = State.BidsMade;
        }
        else {
            if (state == State.BidsMade) {
                //if the newBid is > than the current Bid
                if (msg.value > maxBidAmount) {
                    //1. TODO: fill this in.
                    maxBidder = msg.sender;
                    maxBidAmount = msg.value;
                }
                else {
                    //2. TODO: return the newBid money to the bidder,
                    //   since the newBid wasn't high enough.
                    //   You may call any other functions as needed.
                    msg.sender.transfer(msg.value);
                }
            }
            else {
                revert ("Can only make a bid on an open auction.");
            }
        }
    }
```

Forgot refund!

Neglects withdrawal pattern

(P48)

RANDOMIZED CONTROLLED TRIAL

- Is Obsidian *better* than Solidity?

	Solidity (N=10)	Obsidian (N=10)
Finished in 30 mins	9	8
Correct answer	2	7

2 of these initially lost assets, but fixed after compiler errors

($p \approx 0.09$)

```
Variable 'maxBid' is an owning reference to an
asset, so it cannot be overwritten.
```

RESULTS: SUMMARY

- Considering all three tasks, mean numbers of successful task completions:
  - Solidity: 0.5 tasks
  - Obsidian: 1.5 tasks

OBSIDIAN CONCLUSIONS

- PLIERS grounded Obsidian's design in user data
- Obsidian enabled Java programmers to use typestate and assets after only 90 minutes of training
- Obsidian safety:
  - No invocations on contracts when they are in inappropriate states (e.g., DAO bug)
  - No asset loss bugs (as seen in lab studies)

CONCLUSION

IMPLICATIONS (FOR PL)

- Maximizing expressiveness may conflict with maximizing usability
  - More complex languages produce more varied kinds of failures
  - Asking users to understand the compiler is usually unreasonable
  - *First* optimize for usability, *then* for expressiveness
- Clarity over brevity
- The first design is rarely best
  - Usability studies should accompany every usability claim

IMPLICATIONS (FOR HCI)

- Expert tools benefit from usability studies too
- Methods require only a little adaptation
  - Think-aloud requires probing
  - Adapting questions to familiar contexts focuses studies, improves feasibility
- Reducing stress may be more important to users than saving time

ADOPTION

- Maybe people adopt languages for reasons *unrelated* to language quality.
  - Therefore, maybe we should be focusing on making good languages more adoptable.
- But: people DO create, modify, and adopt languages regularly.
- My focus: enable designers to create better languages.
  - Then, whatever languages get adopted will be better.