ANOSY:
Approximated K**no**wledge **Sy**nthesis with Refinement Types

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Anosy @ PLDI'22

Haskell: Pure with Monads

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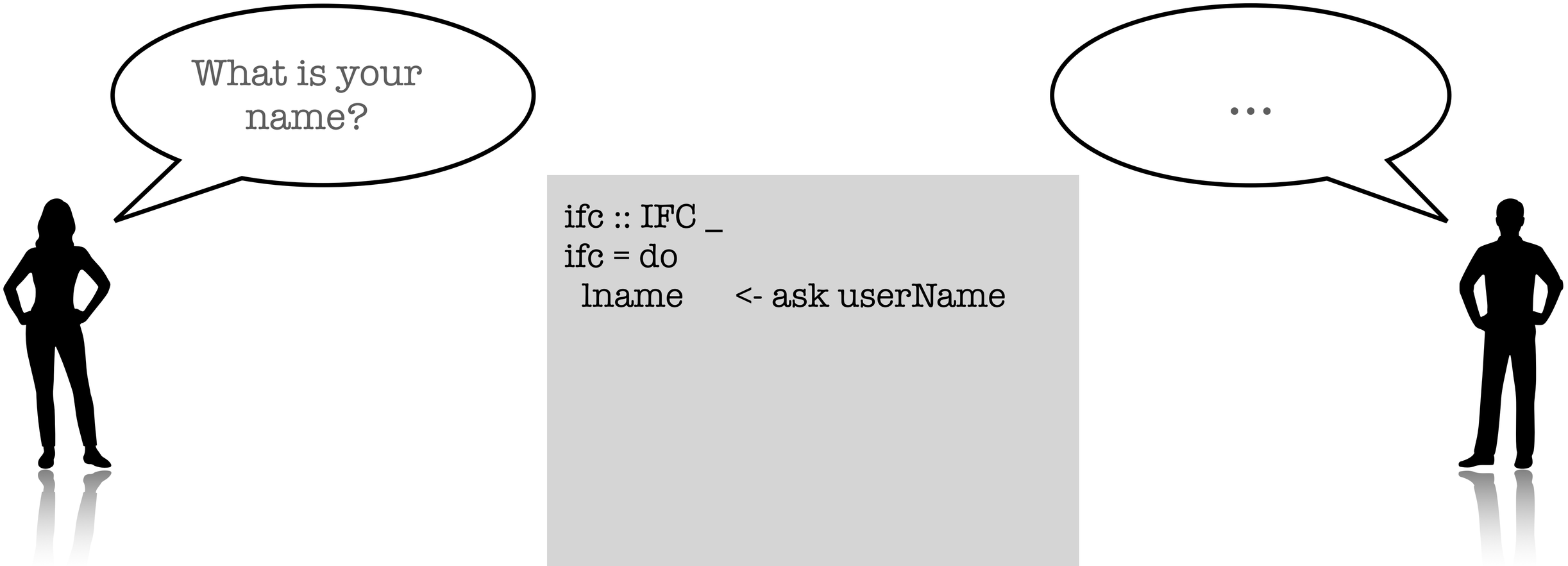
Ideal to track information that goes in the monad

a.k.a. Information Flow Control

Monadic Information Flow Control

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ifc = do
  lname     <- ask userName
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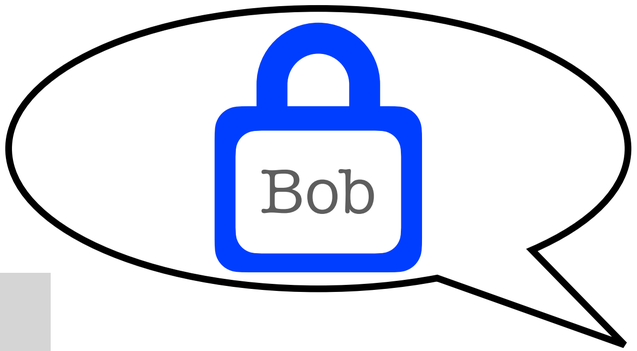

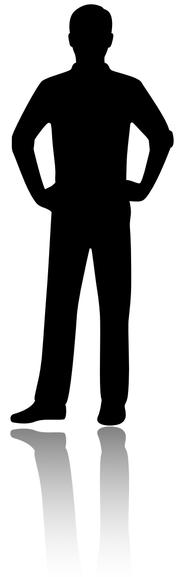

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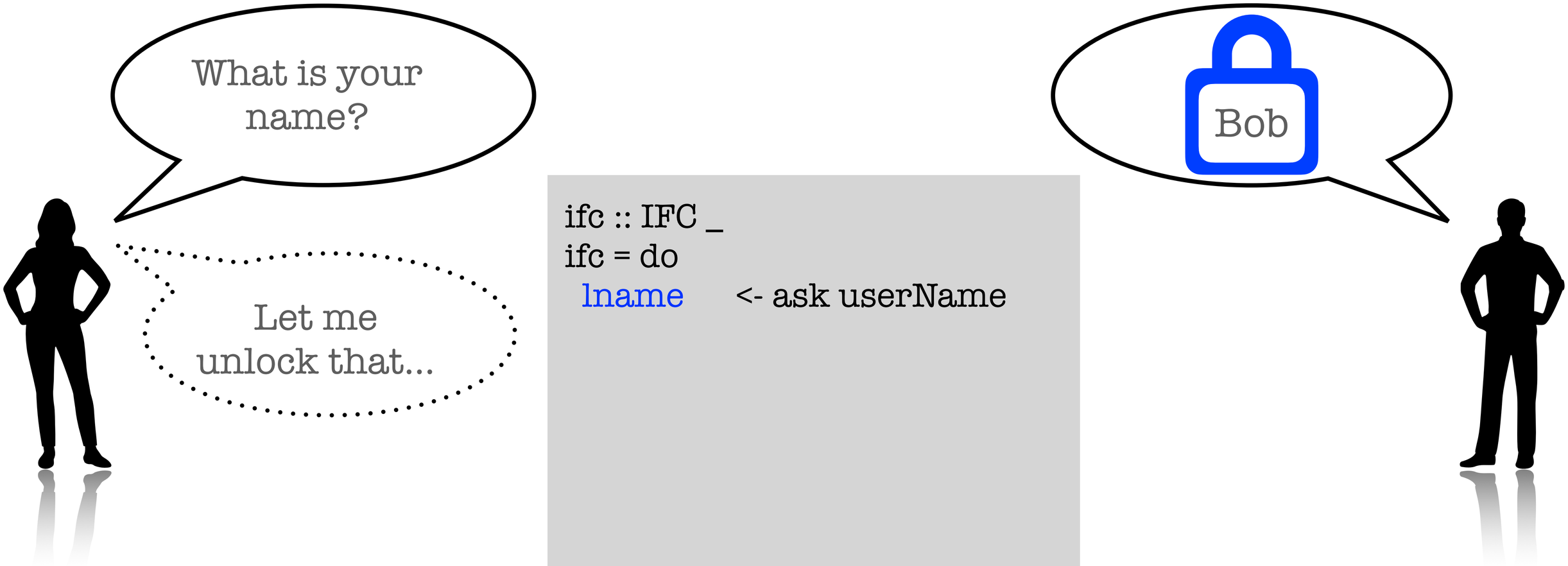


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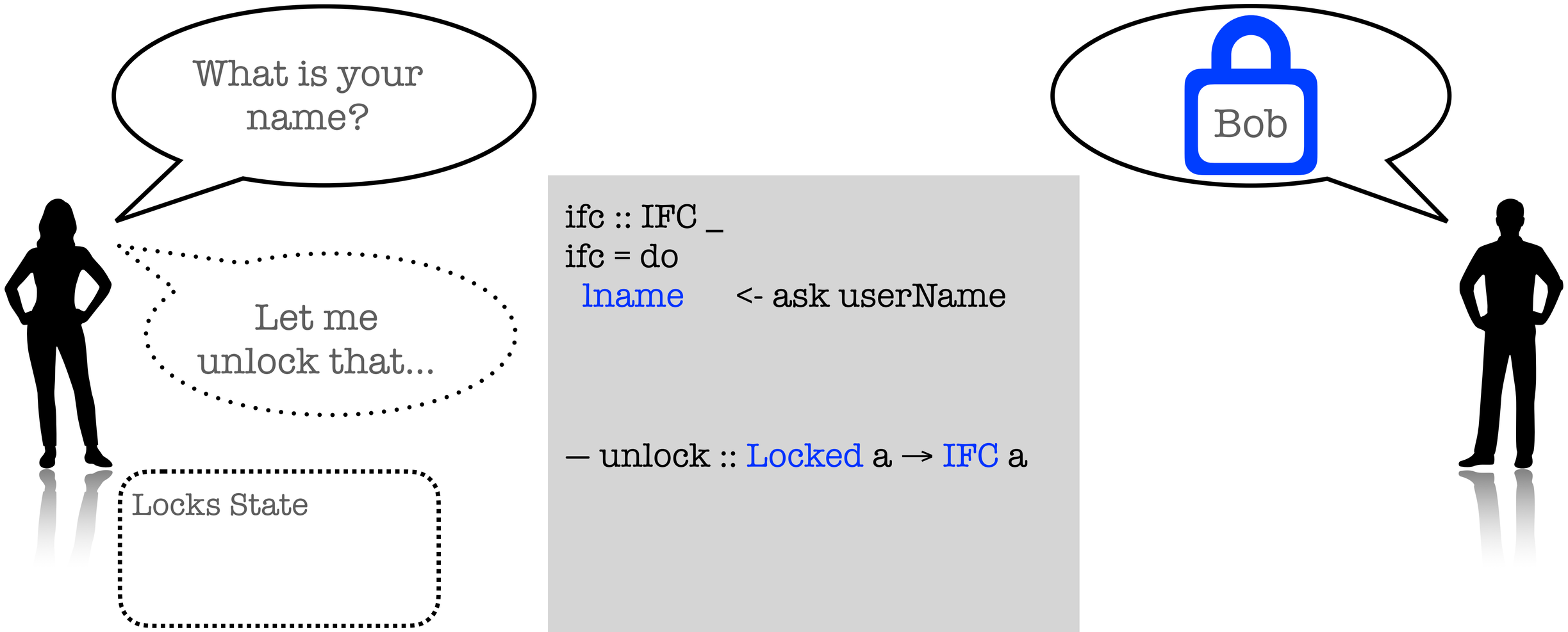


```
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ifc = do
  lname     <- ask userName



— unlock :: Locked a → IFC a
```
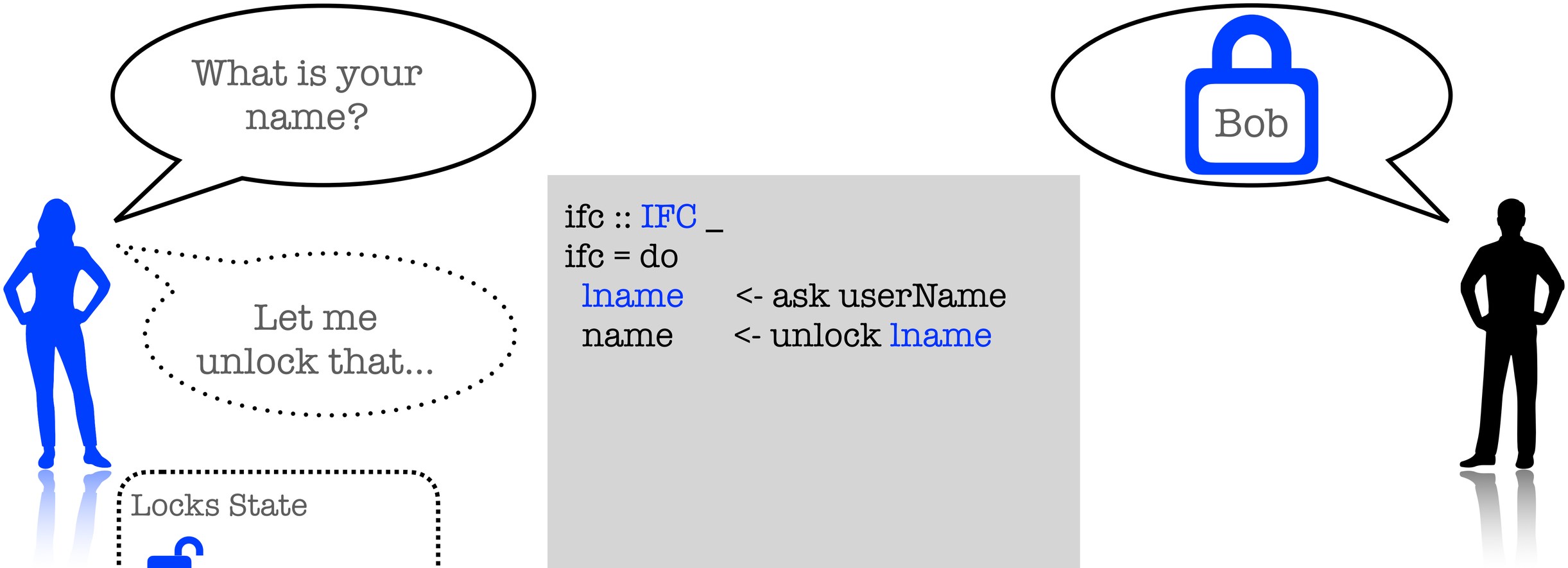
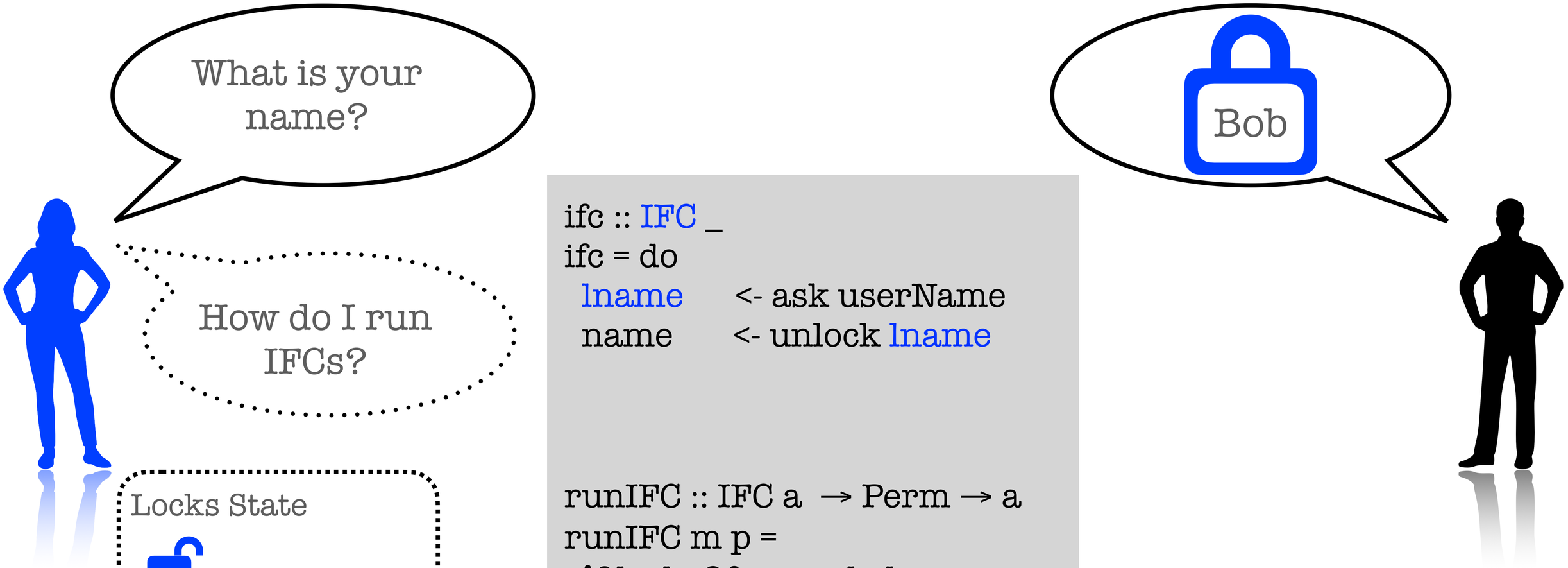

Monadic Information Flow Control




```
ifc :: IFC _
ifc = do
  lname     <- ask userName
  name      <- unlock lname
```

Monadic Information Flow Control

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runIFC :: IFC a  → Perm → a
runIFC m p =
  if locksOf m are below p
    then valueOf  m
    else Permission Error
```

Monadic Information Flow Control


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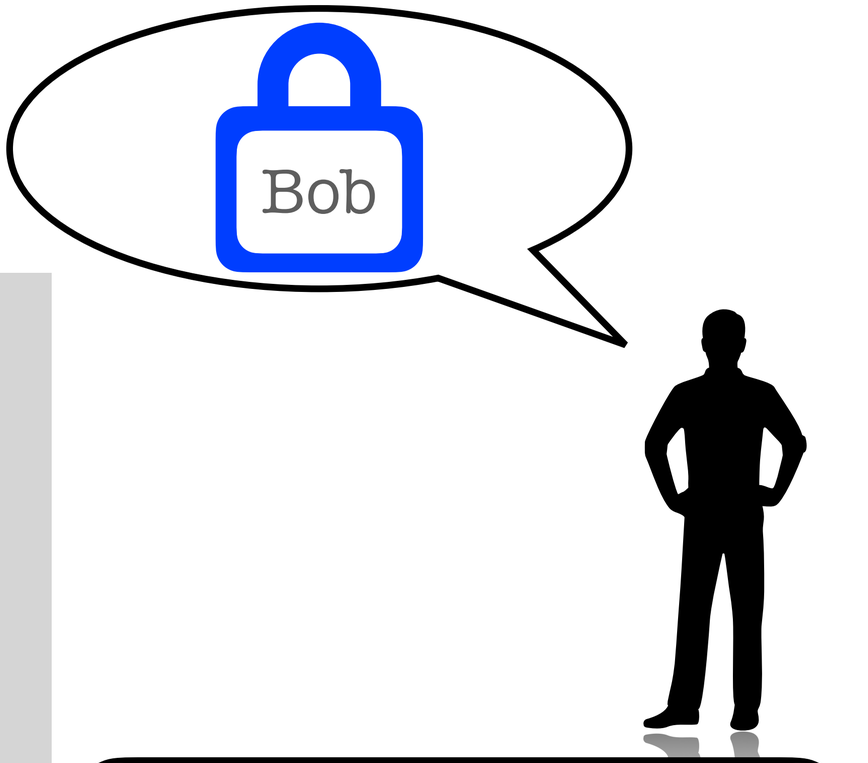
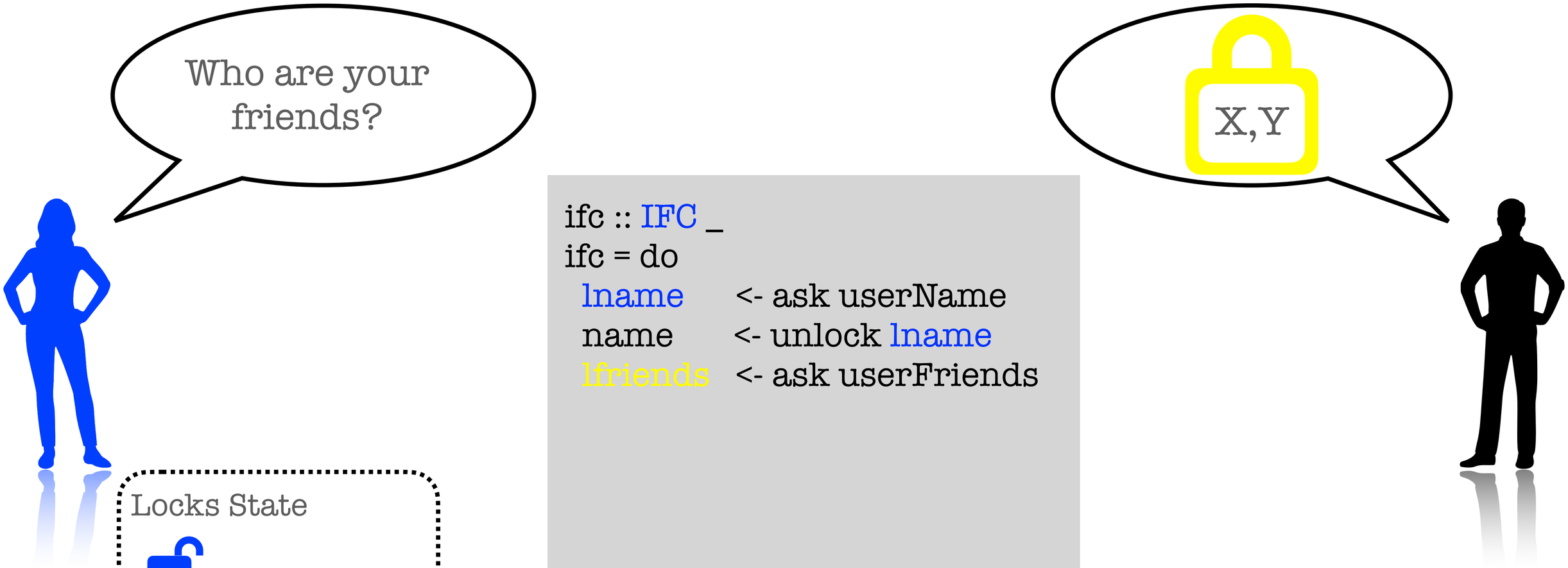


Haskell IFC systems:
LIO, LWeb, STORM

Monadic Information Flow Control

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ifc :: IFC _
ifc = do
  lname     <- ask userName
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  lfriends  <- ask userFriends
```
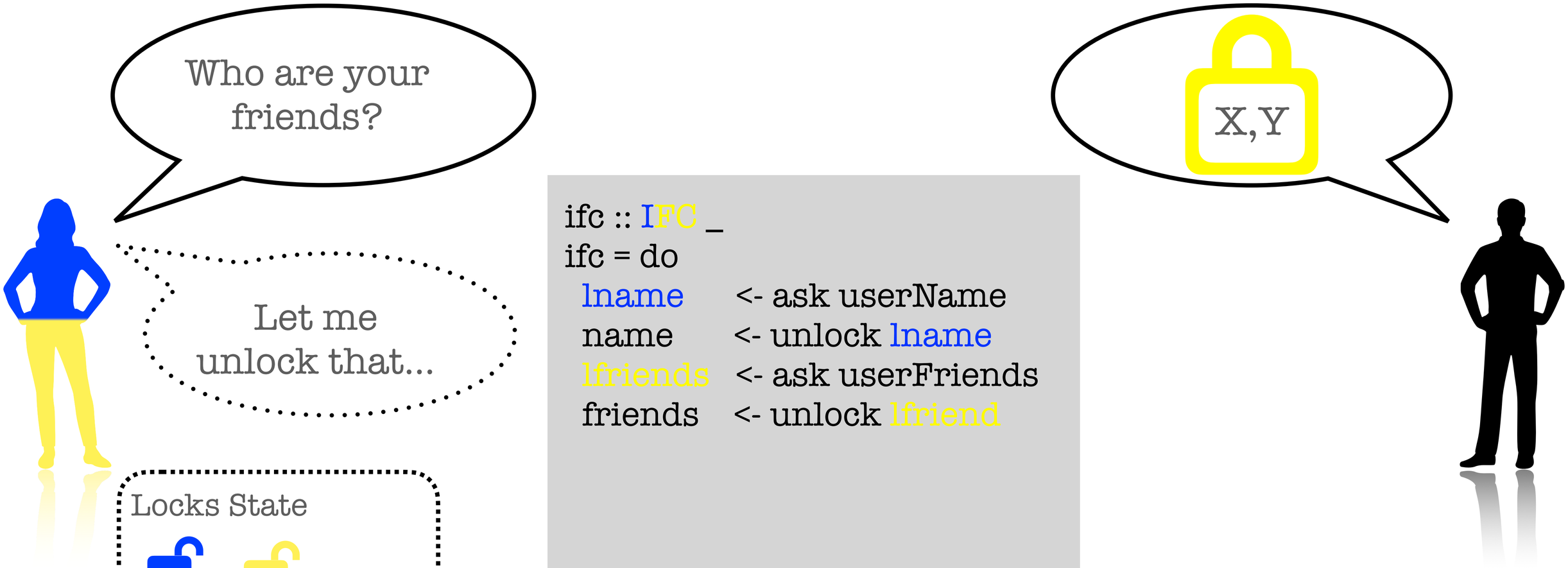

Monadic Information Flow Control

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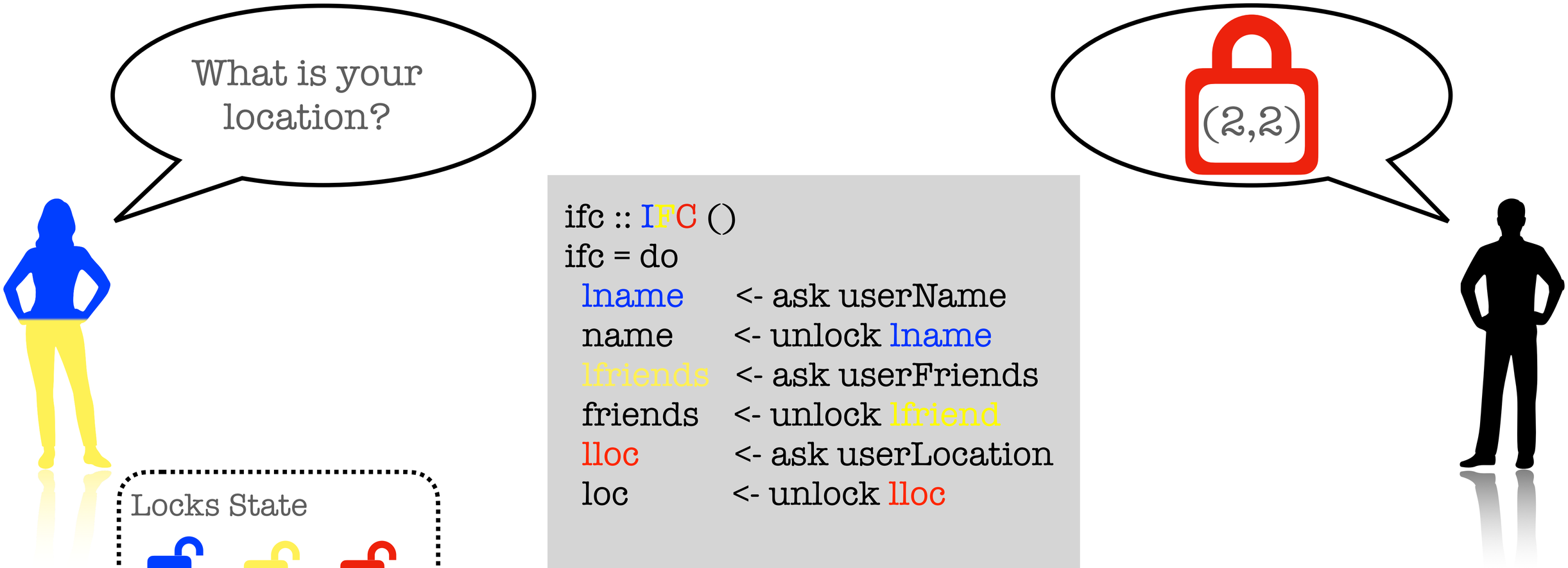
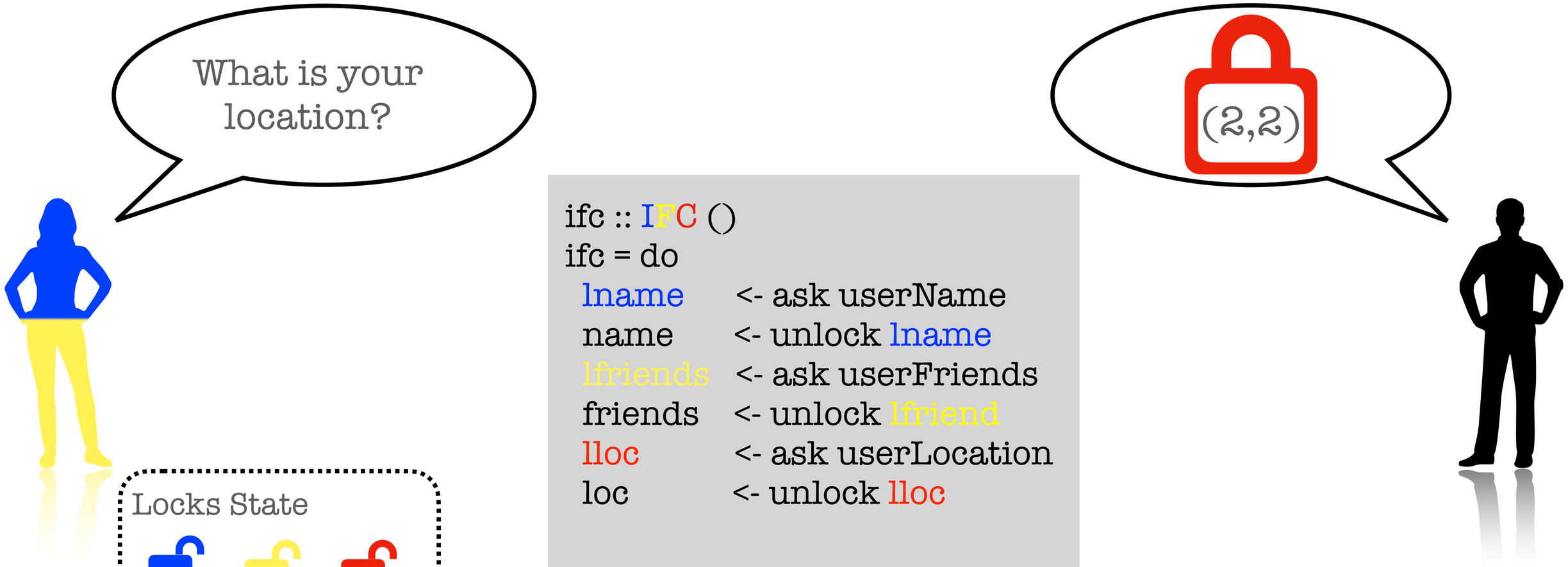



```
ifc :: IFC ()
ifc = do
  lname     <- ask userName
  name      <- unlock lname
  lfriends  <- ask userFriends
  friends   <- unlock lfriend
  lloc      <- ask userLocation
  loc       <- unlock lloc
```

Exact Location is usually Well Protected

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  lname     <- ask userName
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>> runIFC ifc p
>> Permission Error
```

Approximate Location is Required by Location-Based Apps

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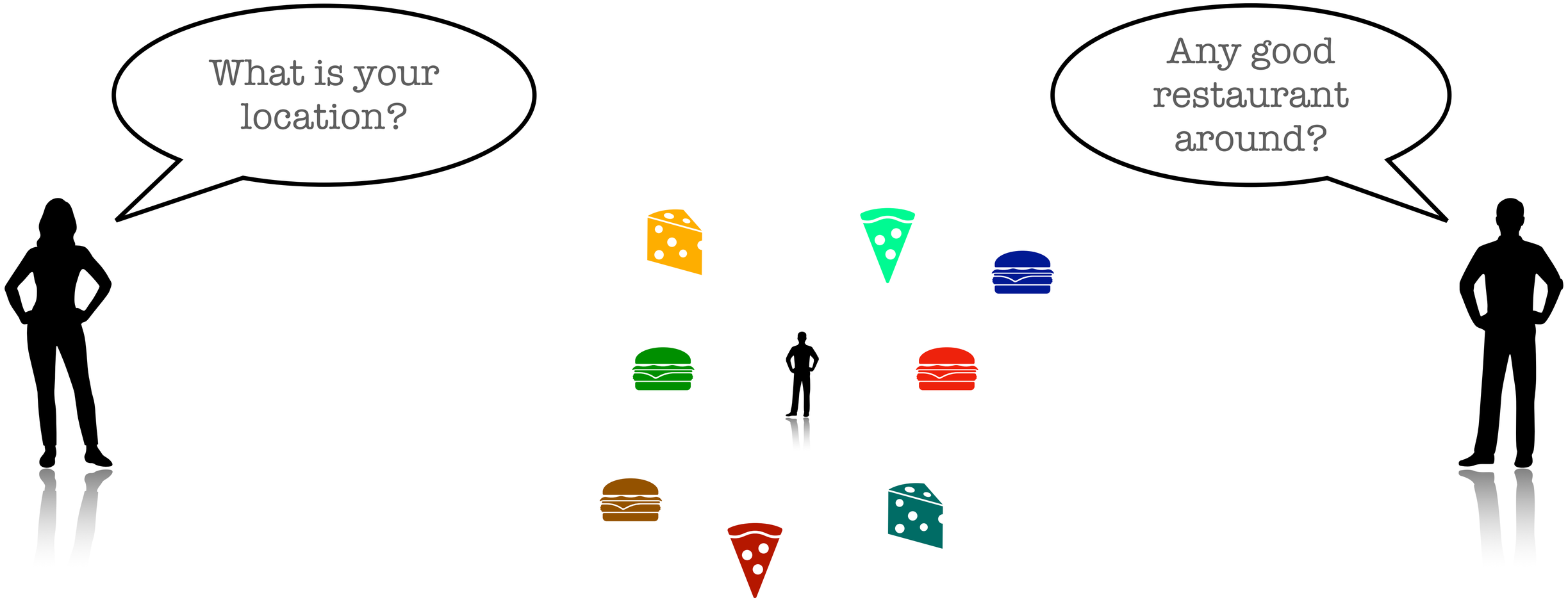

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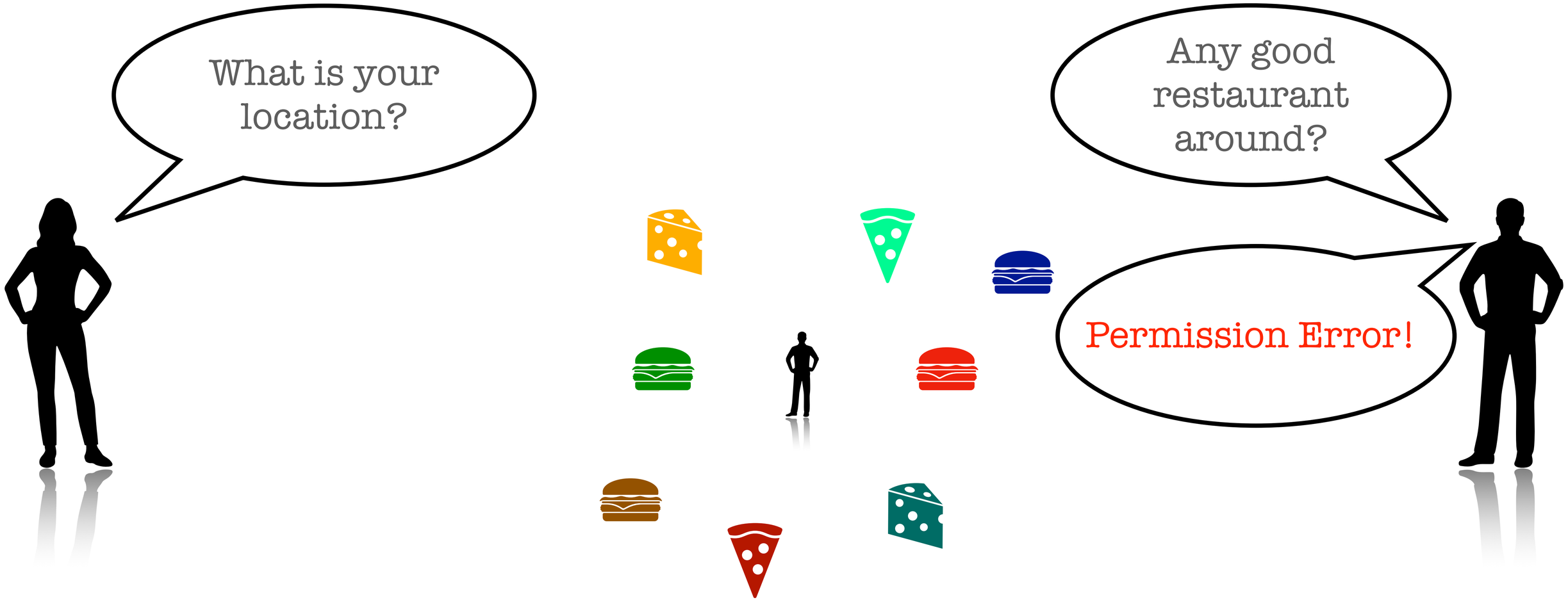

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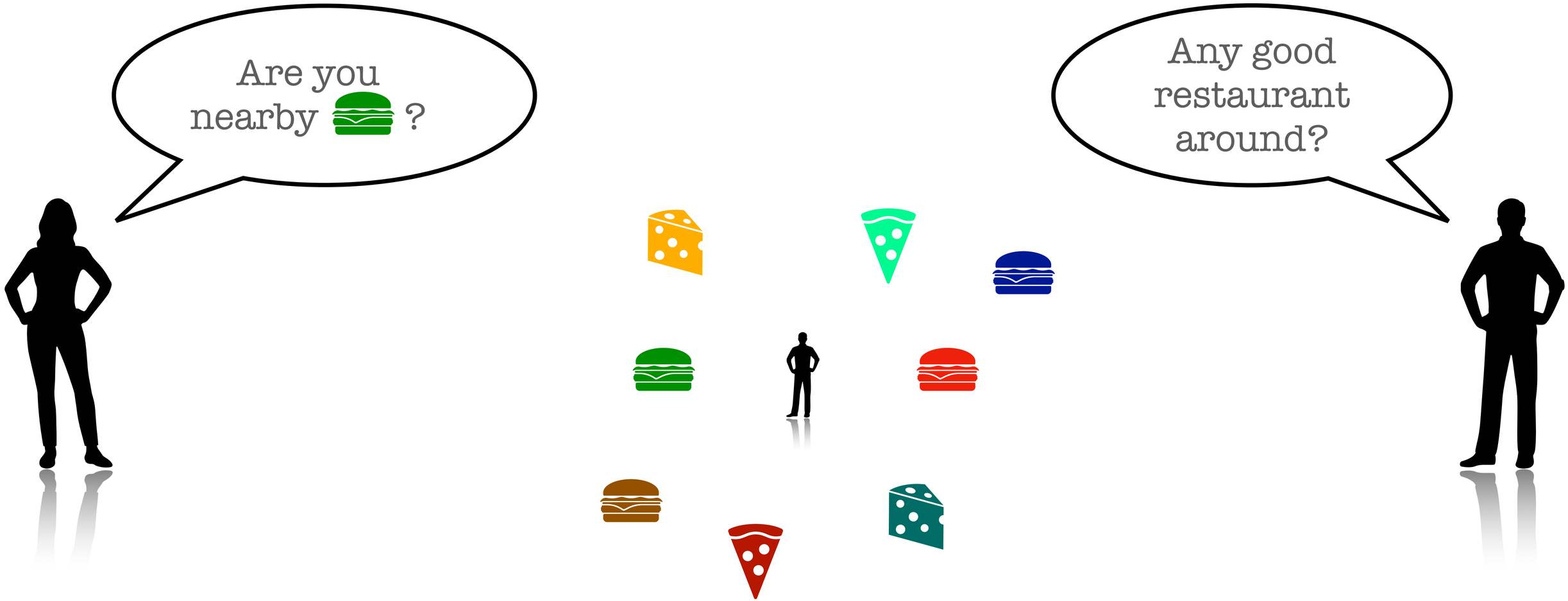
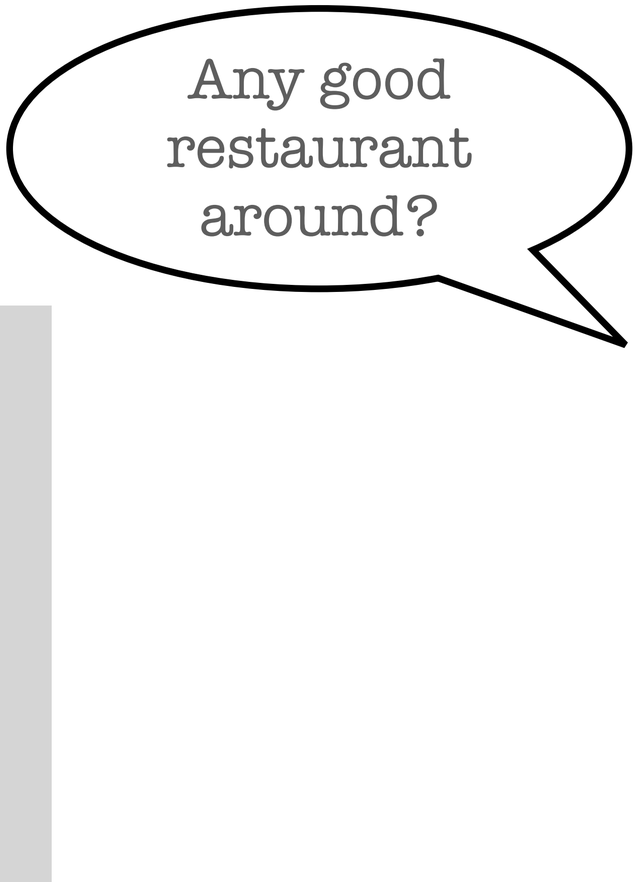


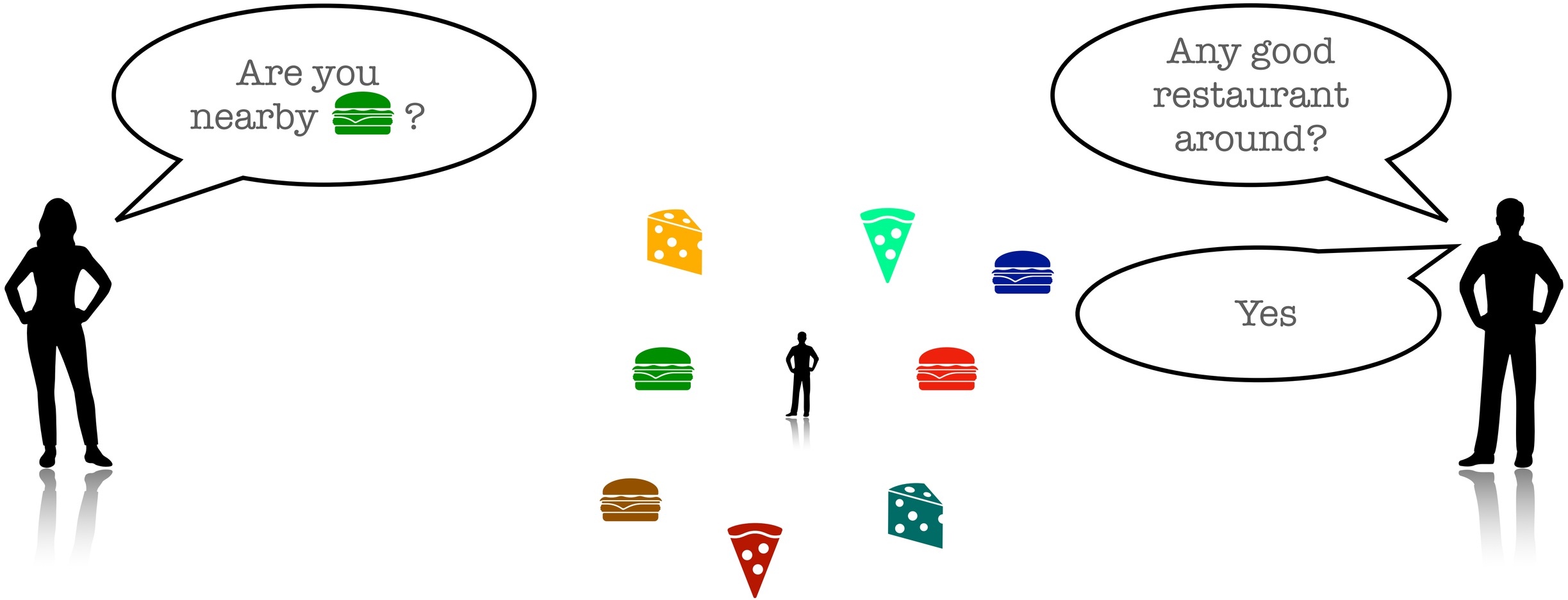
Downgrade for Approximate Location Information




```
ifc :: IFC Bool
ifc = do
  lloc      <- ask userLocation
  isclose   <- downgrade lloc
                         nearbyPlace


downgrade :: Locked s
                  → (s → Bool)
                  → IFC Bool
```

Downgrade for Approximate Location Information



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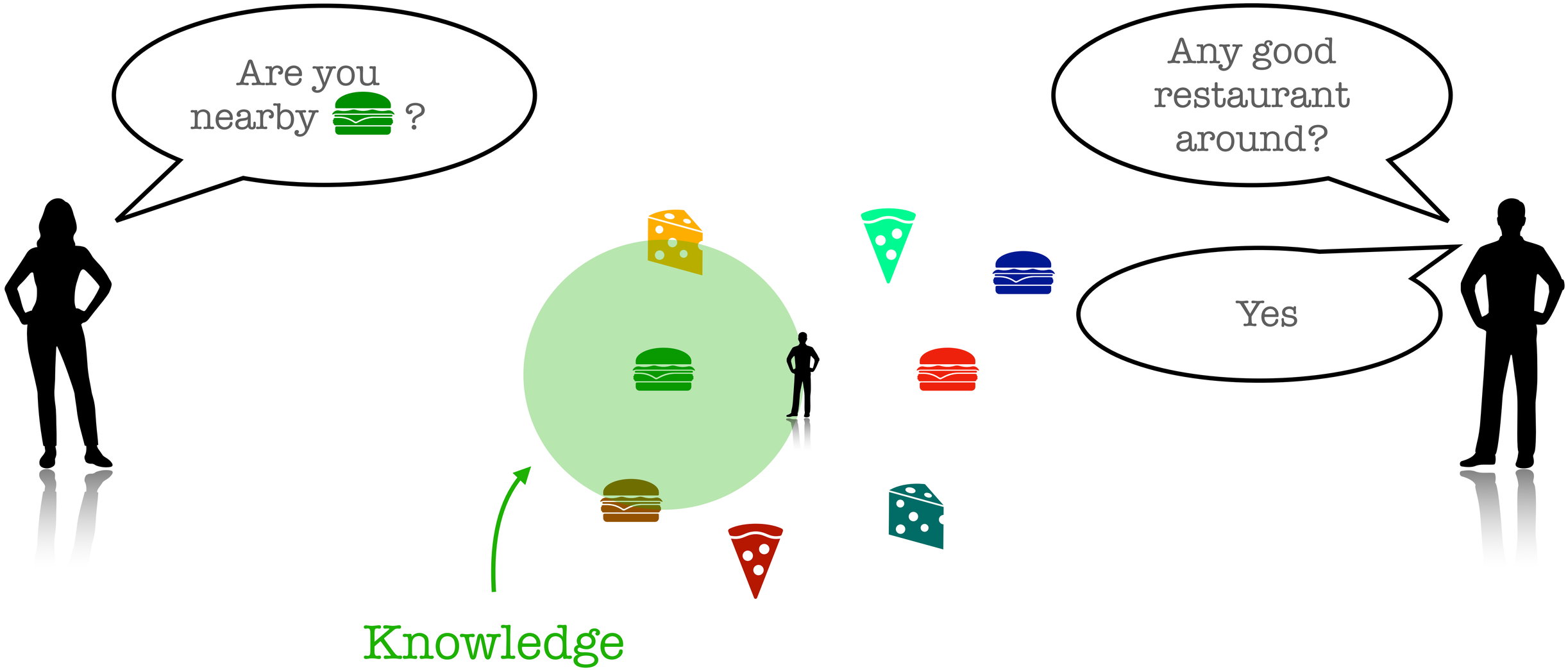

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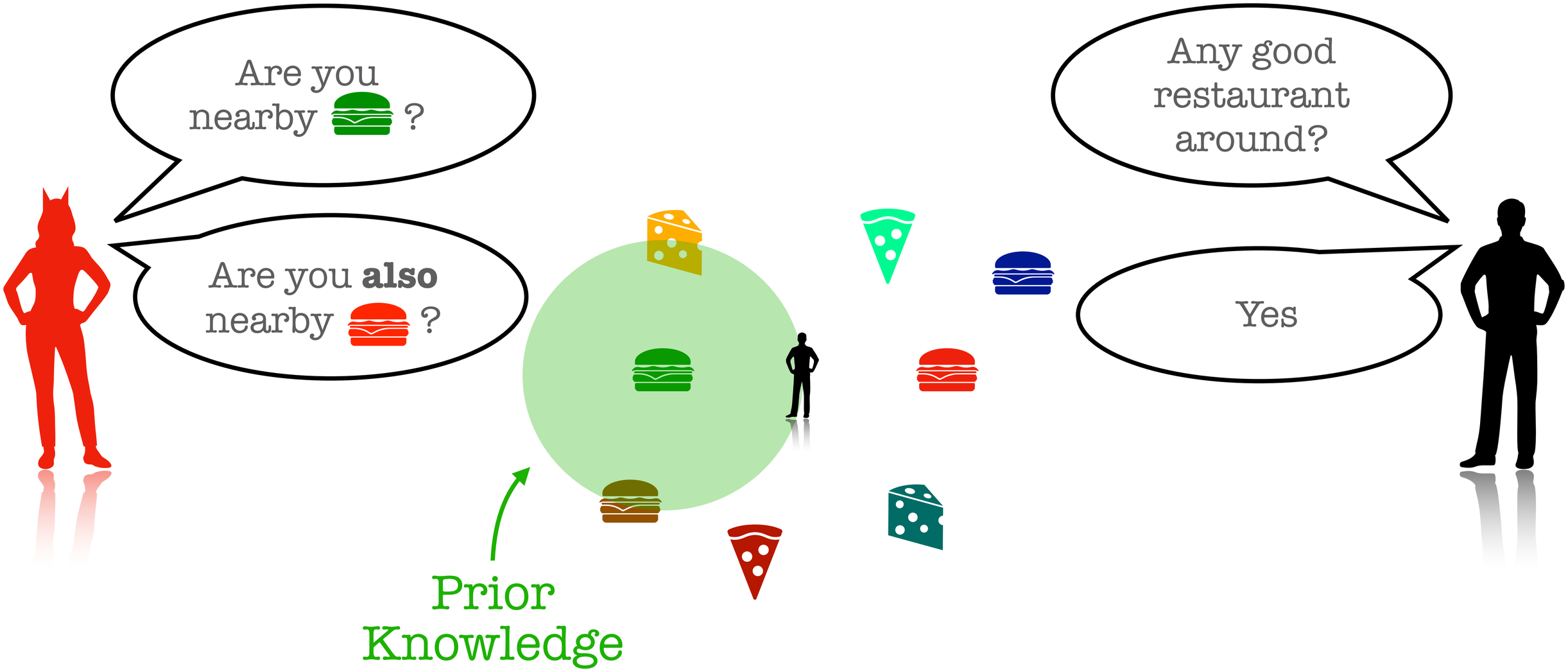

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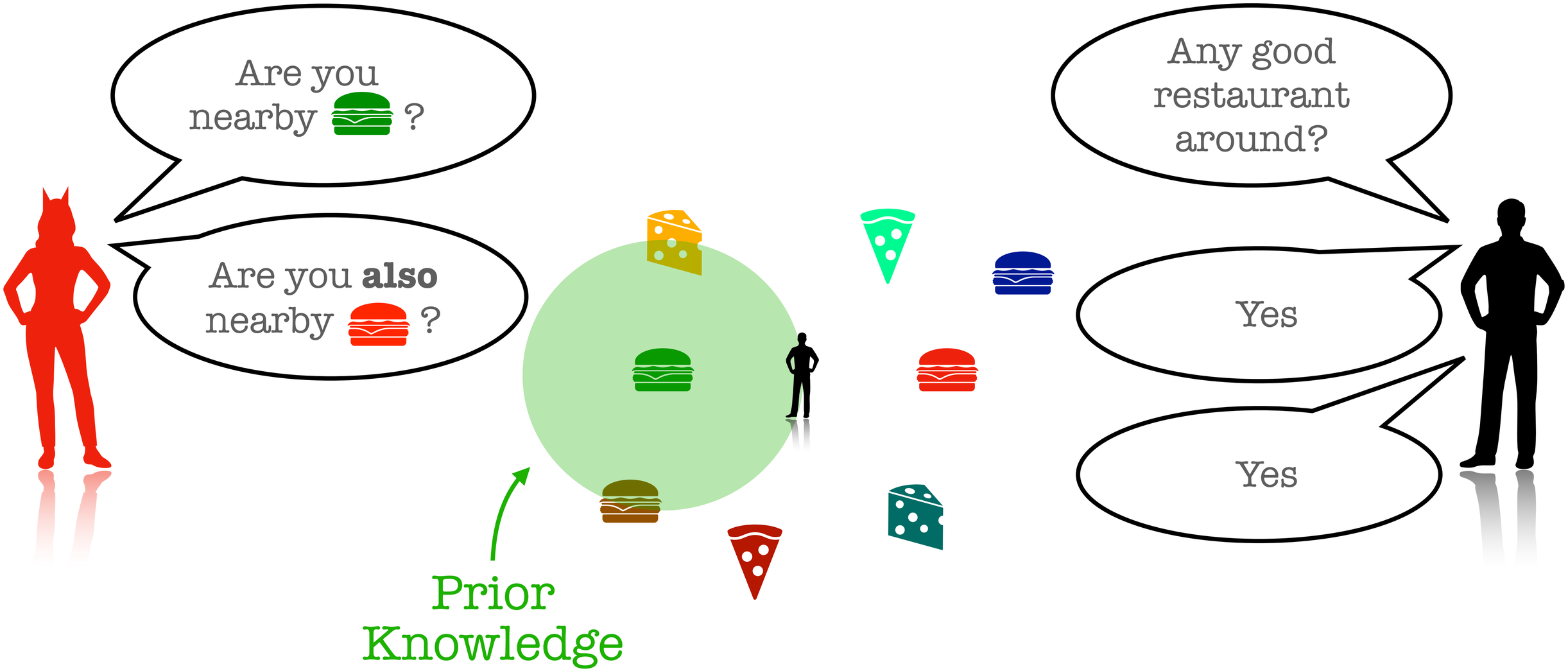

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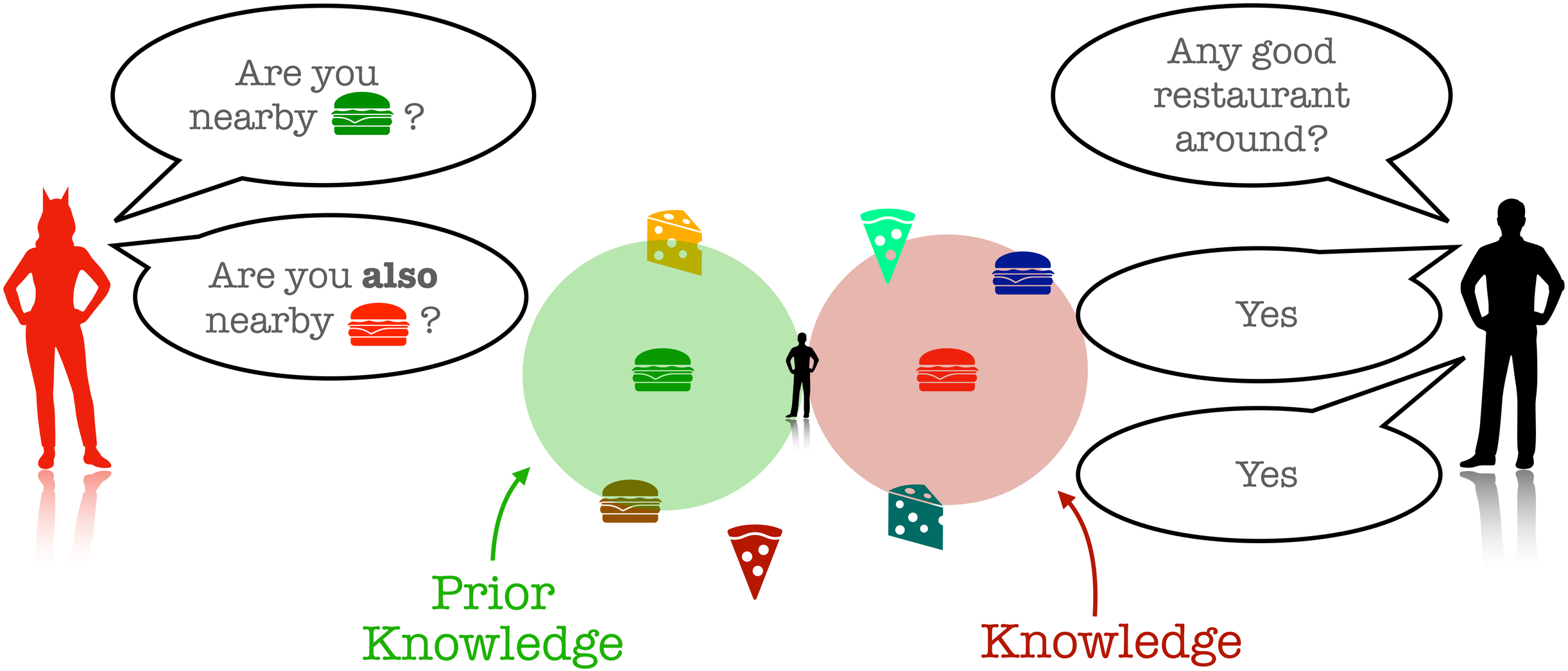

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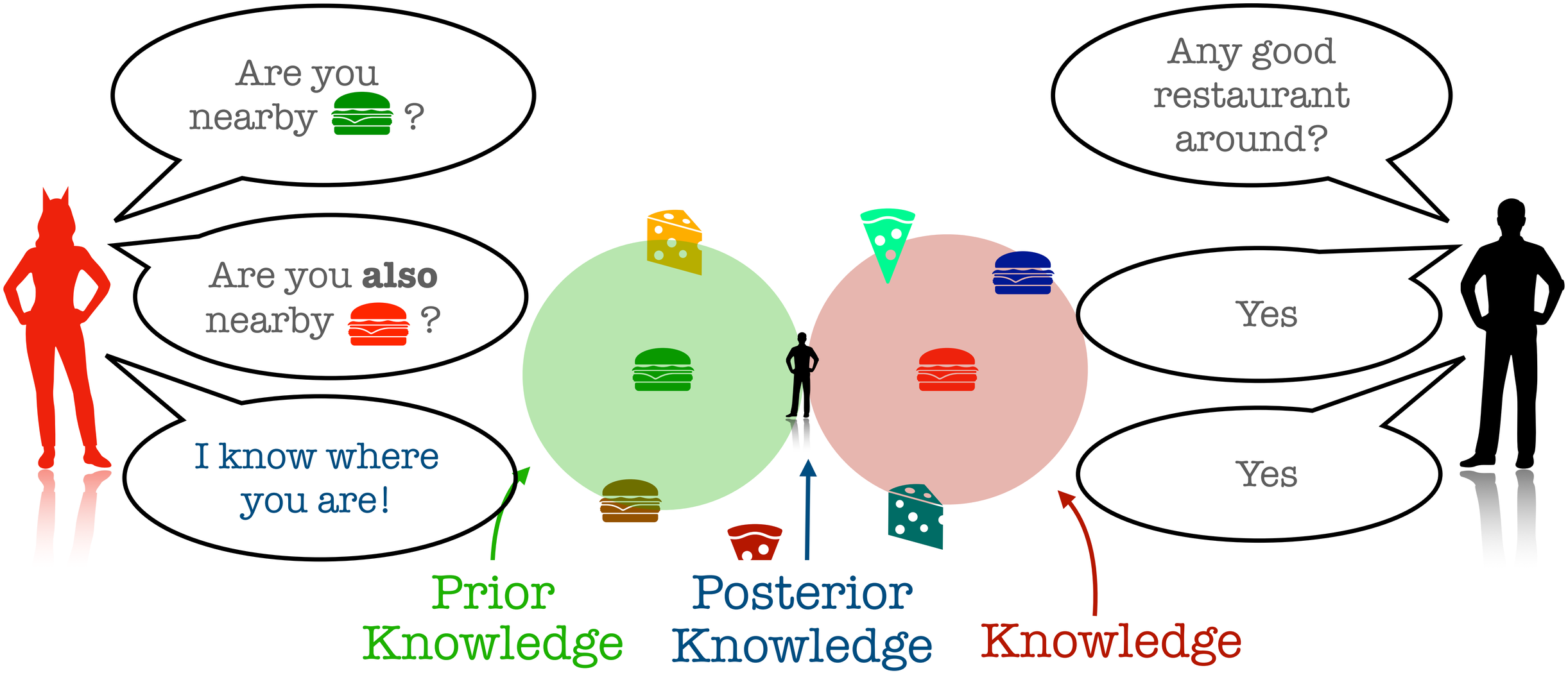

Problem: Downgrade can Leak Exact Location

Bounded Downgrade:
Answer only when posterior is “general enough”

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Bounded Downgrade:
Answer only when posterior is “general enough”

```
policy :: a → Bool
policy a = size a > 100
```

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Answer only when posterior is “general enough”

State

```
priors :: Map s a
policy :: a -> Bool
```

```
downgrade :: Knowledge a s
                  => Locked s
                  → (a → Bool)
                  → IFC Bool
downgrade s q = do
  val      <- unprotect s
  prior    <- getPrior val
  let post = posterior q val prior
  if policy post
    then do setPrior val post
                  return $ q val
    else throwError “Policy Violation”
```

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Observations:

No Dependence from IFC!

How to compute posterior?

Bounded Downgrade: AnosyT Monad Tranformer

```
AnosyT a s =
  StateT (StateA a s)
```

```
StateA

  priors :: Map s a
  policy :: a -> Bool
```

```
downgrade :: Knowledge a s, Monad m
                  , Lockable l => l s
                  → (a → Bool)
                  → AnosyT a s m Bool
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On top of any Haskell IFC system: LIO, LWeb, STORM

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How to compute posterior?

Posterior Knowledge Computation

Goal: Definition of

```
posterior :: Knowledge a s
          => (s → Bool)    — query
          → s              — secret
          → a              — prior
          → a
```

Posterior Knowledge Computation

Knowledge: A Set of Secrets

```
class Knowledge a s where
  ⊤ :: a
  ⊥ :: a
  ∈ :: s → a → Bool
  ⊆ :: a → a → Bool
  ∩ :: a → a → a
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Goal: Definition of

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          => (s → Bool)    — query
          → s              — secret
          → a              — prior
          → a
```

Challenge:

Precise Operations can be Uncomputable

Solution:

Use Abstract Domains!

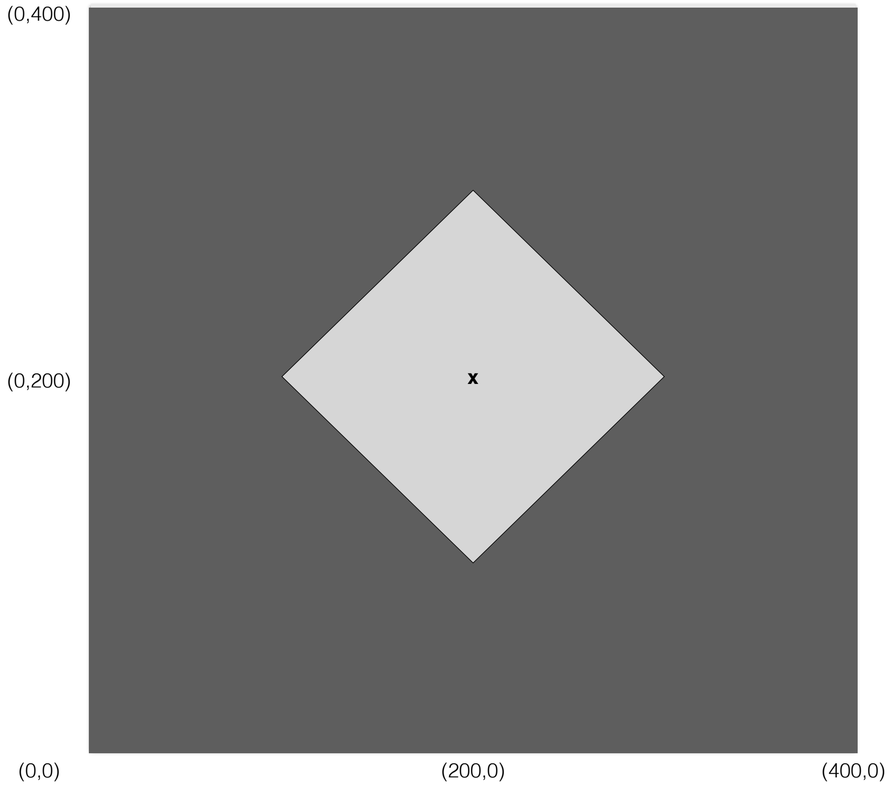
Knowledge Representation

```
data Loc = L {x :: Int, y :: Int}

nearby :: Loc  → Loc → Bool
nearby (L xo yo) (L x y) =
  abs (x - xo) (y -yo) <= 100
```

```
type S = Loc

query :: S → Bool
query s = nearby (L 200 200)
```



Knowledge on query
(Separation into yes/no areas)

Knowledge Representation

Difficult to Represent

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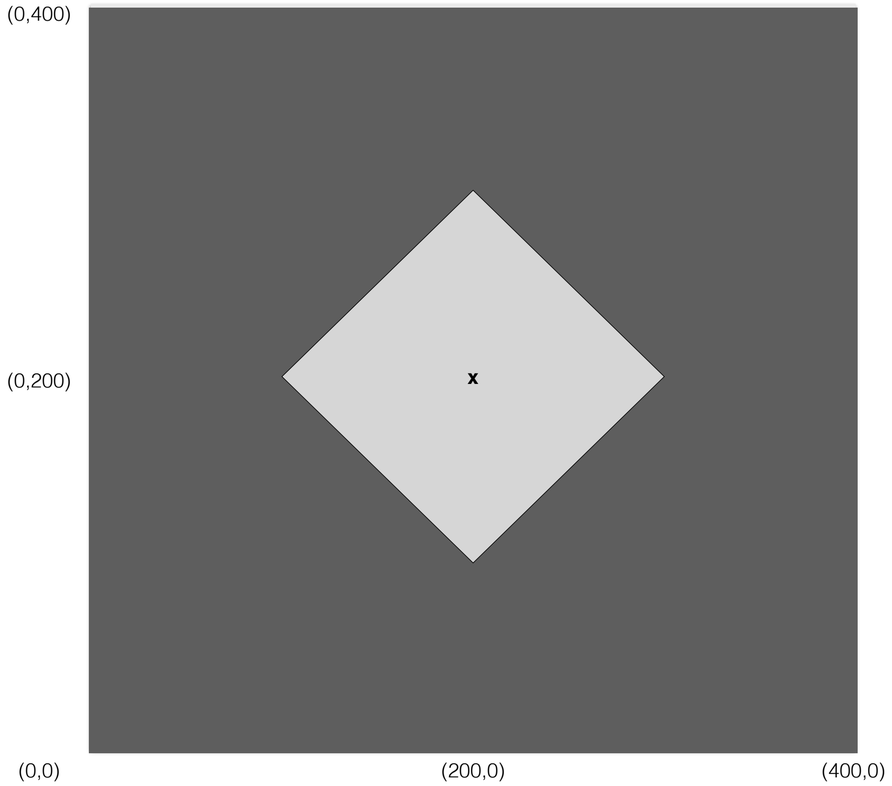


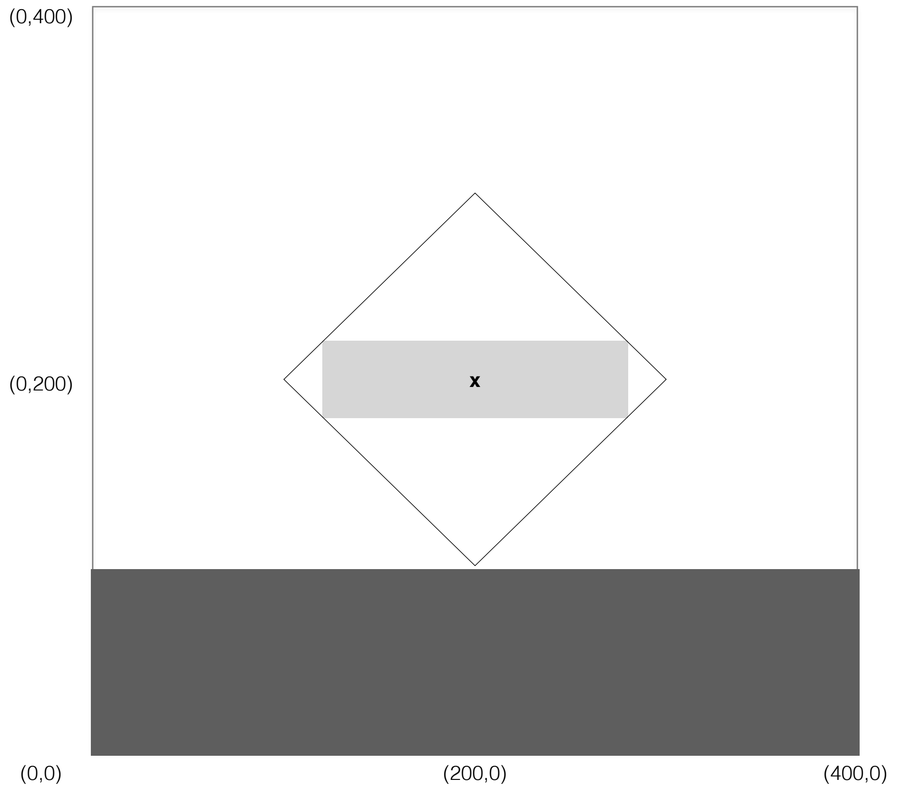
Knowledge on query
(Separation into yes/no areas)

Knowledge Approximation

```
type S = Loc —  = L {x :: Int, y :: Int}
query :: S → Bool
query s = nearby (L 200 200)
```

```
data KInt = KInt {lo :: Int, hi :: Int}
data K    = K {kx :: KInt, ky :: KInt}
instance Knowledge K S where ...
```

```
approx :: (K,K)
approx = (yesK, noK)
yesK = K (KInt 121 279) (KInt 179 221)
noK  = K (KInt 0   400)  (KInt 0   99)
```



Interval Knowledge Approximation

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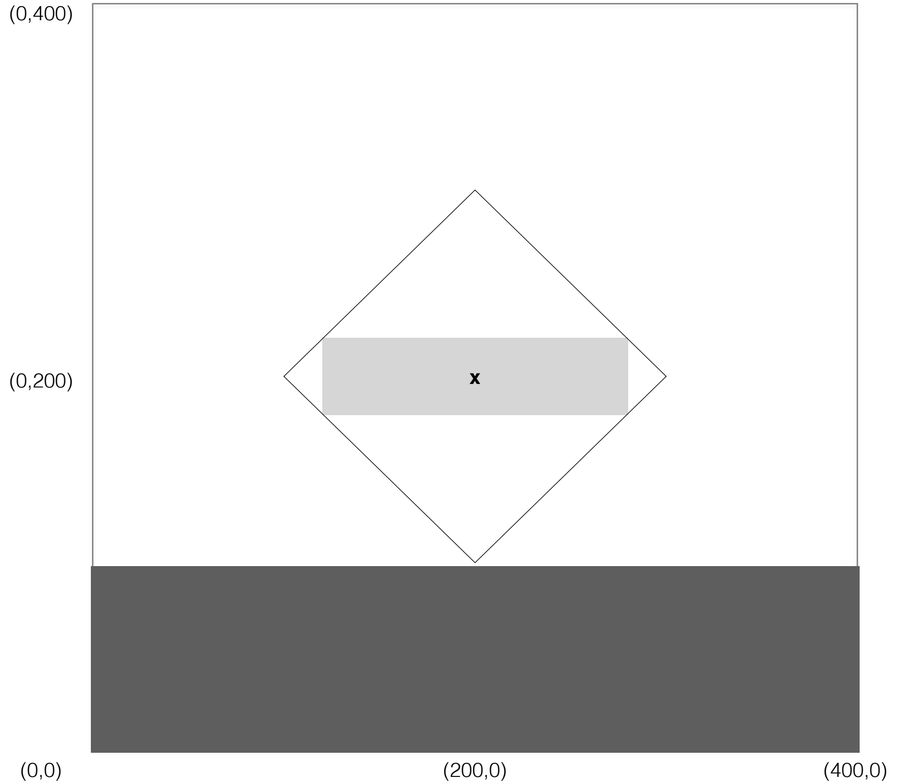
Back to our Goal, posterior is easy to define

```
posterior :: S → K → K
posterior s p = p ∩
  if query s then  yesK else noK
```



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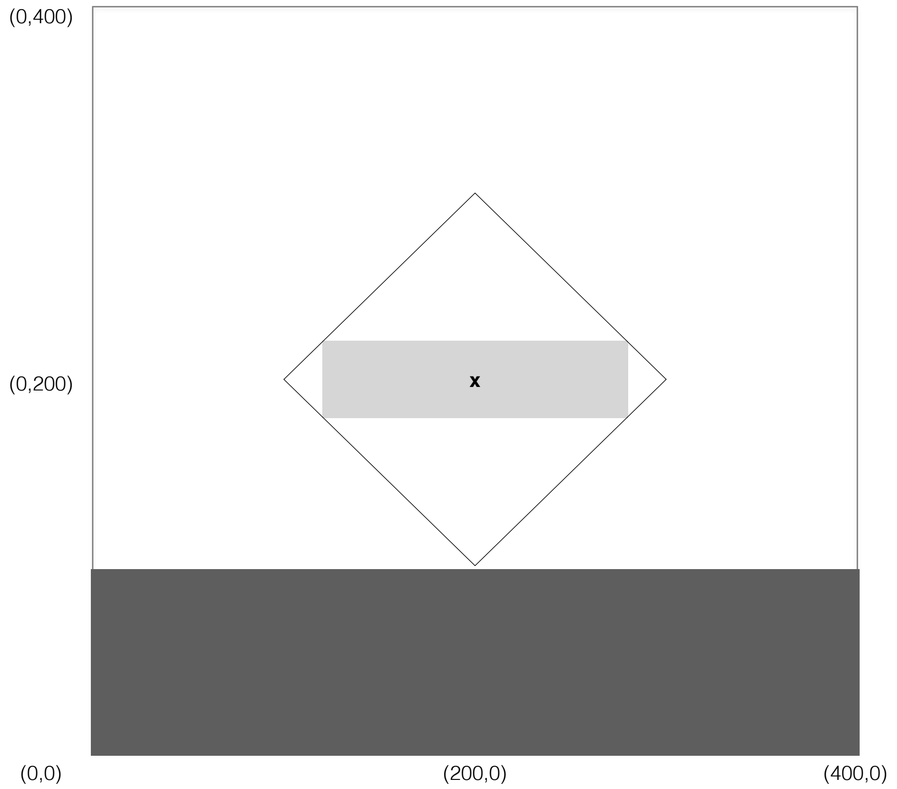

Interval Knowledge Approximation

How do I come up with approx?

How do I know it is correct?

Refinement Types to the Rescue!

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approx = (yesK, noK)
yesK = K (KInt 121 279) (KInt 179 221)
noK  = K (KInt 0   400) (KInt 0   99)
```

```
yesK :: K<\s -> query s>
noK  :: K<\s -> not (query s)>
```

k :: K<p>

All elements inside* k satisfy p

* Knowledge contains secrets

LiquidHaskell

Refinement Types for Synthesis!

Goal: yesK :: K<\s -> query s>

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Step 1: Syntax Directed

```
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Step 2: Constraint Generation

$\forall$ x, y. xl $\leq$ x $\leq$ xh $\wedge$ yl $\leq$ y $\leq$ yh $\Rightarrow$ query (L x y)
maximise xh - xl
maximize yh - yl

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Step 3: SMT solves constraints

xl := 121, xh := 279, yl := 179 , yh := 221

Refinement Types for Synthesis!

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Step 1: Syntax Directed

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Step 3: SMT solves constraints

xl := 121, xh := 279, yl := 179 , yh := 221

Finally: Plug in the holes

yesK = K (KInt 121 279) (KInt 179 221)

Anosy: Bounded Downgrade

AnosyT keeps track of prior leaked knowledge

Challenge: compute posterior
Knowledge Abstraction + Synthesis.

For each query, abstract knowledge is
synthesised via SMT
verified via Liquid Haskell

Implementation

AnosyT + GHC plugin to process queries.

Queries are straight line Bool functions

Secrets are products of Ints

Abstract Domains are Intervals and their Powersets

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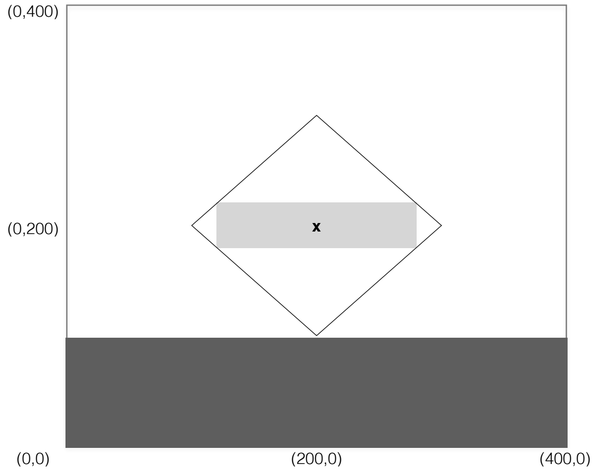
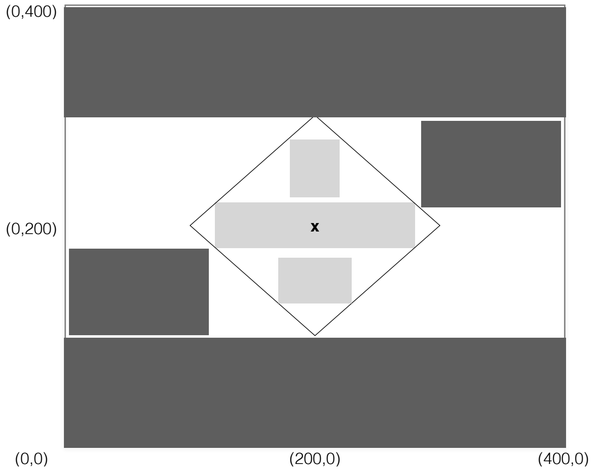


Interval Knowledge



Powerset Knowledge

Evaluation

#	Name	No. of fields	Size of ind. sets
B1	Birthday	2	259 / 13246
B2	Ship	3	1.01e+06 / 2.43e+07
B3	Photo	3	4 / 884
B4	Pizza	4	1.37e+10 / 2.81e+13
B5	Travel	4	2160 / 6.72e+06

We evaluate with secrets with multiple dimensions

#	Under-approximation							
	Size	% diff.	Verif. time	Synth. time				Synth. time
B1	259 / 9620	0 / 27	2.78 ± 0.03	1.11 ± 0.01	259 / 13505	0 / 2	2.64 ± 0.03	1.07 ± 0.01
B2	2.21e+05 / 1.01e+07	78 / 58	3.62 ± 0.02	9.26 ± 0.04	2.02e+06 / 2.54e+07	100 / 5	3.17 ± 0.02	4.00 ± 0.12
B3	4 / 664	0 / 25	3.12 ± 0.06	0.90 ± 0.07	4 / 888	0 / 0	2.83 ± 0.03	0.90 ± 0.01
B4	3.53e+04 / 1.35e+05	100 / 100	3.66 ± 0.04	20.92 ± 0.11	9.22e+12 / 2.81e+13	67200 / 0	3.29 ± 0.08	10.87 ± 0.01
B5	360 / 5.04e+06	83 / 25	3.81 ± 0.04	1.38 ± 0.04	35460 / 6.72e+06	1542 / 0	3.47 ± 0.04	0.89 ± 0.01

(a) Interval abstract domain

#	Under-approximation				Over-approximation			
	Size	% diff.	Verif. time	Synth. time	Size	% diff.	Verif. time	Synth. time
B1	259 / 13246	0 / 0	4.51 ± 0.05	1.13 ± 0.02	259 / 13505	0 / 2	4.34 ± 0.03	1.08 ± 0.01
B2	6.78e+05 / 1.62e+07	33 / 33	5.32 ± 0.09	14.34 ± 0.11	1.80e+06 / 2.54e+07	78 / 5	5.17 ± 0.02	4.89 ± 0.09
B3	4 / 880	0 / 0	5.29 ± 0.09	1.07 ± 0.03	4 / 888	0 / 0	4.99 ± 0.03	1.03 ± 0.01
B4	3.88e+05 / 4.00e+05	100 / 100	5.78 ± 0.03	54.89 ± 0.23	9.22e+12 / 2.81e+13	67200 / 0	5.48 ± 0.08	30.57 ± 0.07
B5	720 / 6.70e+06	67 / 0	6.02 ± 0.07	13.26 ± 0.09	6300 / 6.72e+06	192 / 0	5.96 ± 0.04	15.25 ± 0.03

(b) Powerset of intervals with size 3

* Mardziel, Magill, Hicks, and Srivatsa. J. Comp. Sec. 2013. Dynamic enforcement of knowledge-based security policies using probabilistic abstract interpretation.

Evaluation

#	Name	No. of fields	Size of ind. sets
B1	Birthday	2	259 / 13246
B2	Ship	3	1.01e+06 / 2.43e+07
B3	Photo	3	4 / 884
B4	Pizza	4	1.37e+10 / 2.81e+13
B5	Travel	4	2160 / 6.72e+06

#	Under-approximation				Over-approximation			
	Size	% diff.	Verif. time	Synth. time	Size	% diff.	Verif. time	Synth. time
B1	259 / 9620	0 / 27	2.78 ± 0.03	1.11 ± 0.01	259 / 13505	0 / 2	2.64 ± 0.03	1.07 ± 0.01
B2	2.21e+05 / 1.01e+07	78 / 58	3.62 ± 0.02	9.26 ± 0.04	2.02e+06 / 2.54e+07	100 / 5	3.17 ± 0.02	4.00 ± 0.12
B3	4 / 664	0 / 25	3.12 ± 0.06	0.90 ± 0.07	4 / 888	0 / 0	2.83 ± 0.03	0.90 ± 0.01
B4	3.53e+04 / 1.35e+05	100 / 100	3.66 ± 0.04	20.92 ± 0.11	9.22e+12 / 2.81e+13	67200 / 0	3.29 ± 0.08	10.87 ± 0.01
B5	360 / 5.04e+06	83 / 25	[illegible]	1.38 ± 0.04	35460 / 6.72e+06	1542 / 0	3.47 ± 0.04	0.89 ± 0.01

Synthesis times are reasonable. Static analysis tools such as Prob* are faster. But ANOSY synthesises knowledge at compile time.

Interval abstract domain

				Over-approximation			
			Synth. time	Size	% diff.	Verif. time	Synth. time
			1.13 ± 0.02	259 / 13505	0 / 2	4.34 ± 0.03	1.08 ± 0.01
			14.34 ± 0.11	1.80e+06 / 2.54e+07	78 / 5	5.17 ± 0.02	4.89 ± 0.09
B3	4 / 880	0 / 0	5.29 ± 0.09	1.07 ± 0.03	4 / 888	0 / 0	4.99 ± 0.03	1.03 ± 0.01
B4	3.88e+05 / 4.00e+05	100 / 100	5.78 ± 0.03	54.89 ± 0.23	9.22e+12 / 2.81e+13	67200 / 0	5.48 ± 0.08	30.57 ± 0.07
B5	720 / 6.70e+06	67 / 0	6.02 ± 0.07	13.26 ± 0.09	6300 / 6.72e+06	192 / 0	5.96 ± 0.04	15.25 ± 0.03

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Approximation accuracy gets better with increasing the size of the powerset.

#	Under-approximati				roximation			
	Size	% diff.	Ver		f.	Verif. time	Synth. time	
B1	259 / 13246	0 / 0	4.51 ± 0.05	± 0.02	259 / 13505	0 / 2	4.34 ± 0.03	1.08 ± 0.01
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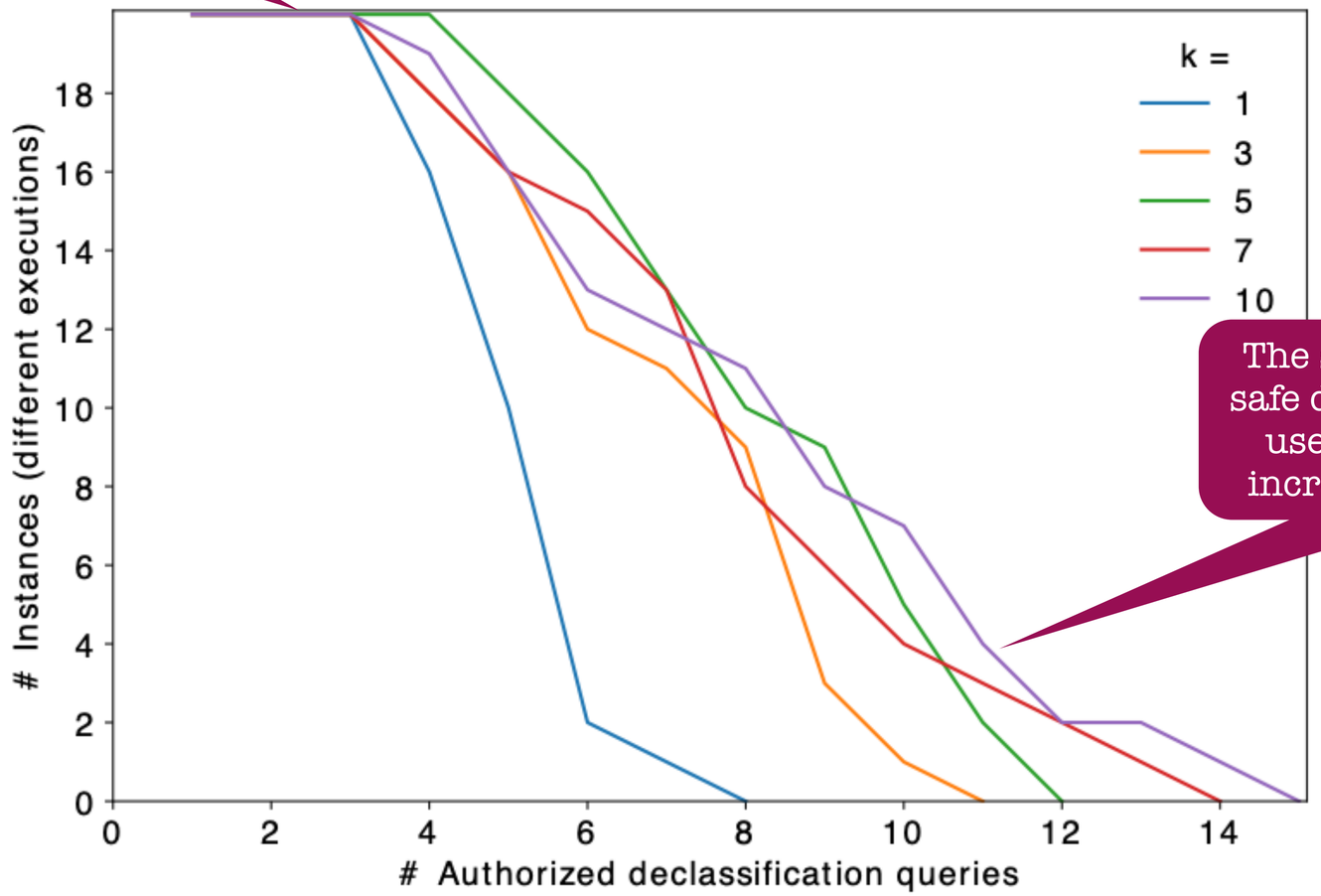
(b) Powerset of intervals with size 3

* Mardziel, Magill, Hicks, and Srivatsa. J. Comp. Sec. 2013. Dynamic enforcement of knowledge-based security policies using probabilistic abstract interpretation.

Evaluation: Location Example

All these queries are verified safe for the nearby query.



The system handles more safe declassifications of if a user is nearby with the increase in powerset size

Summary

Haskell is Ideal for IFC (e.g., LIO, LWeb, STORM)

Realistic IFC apps downgrade (potentially leaking info)

Anosy: Bounded Downgrade

AnosyT keeps track of prior leaked knowledge

For each query, abstract knowledge is
synthesised via SMT
verified via Liquid Haskell

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Anosy @ PLDI

nikivazou

institute imdea software

Looking for
PhDs/interns

Thanks!