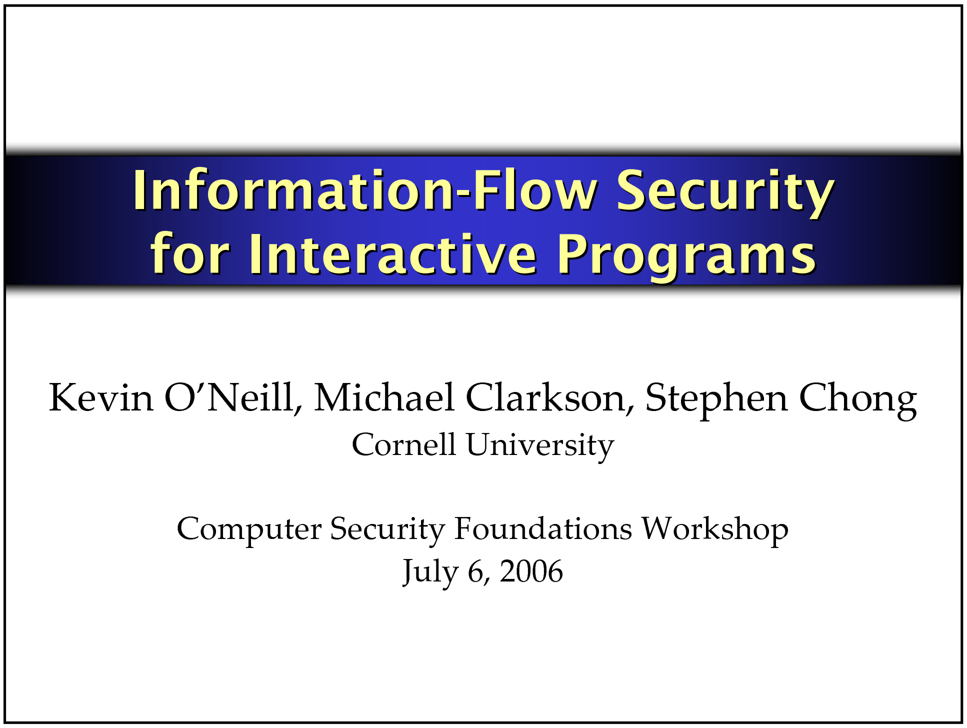

Information-Flow Security for Interactive Programs

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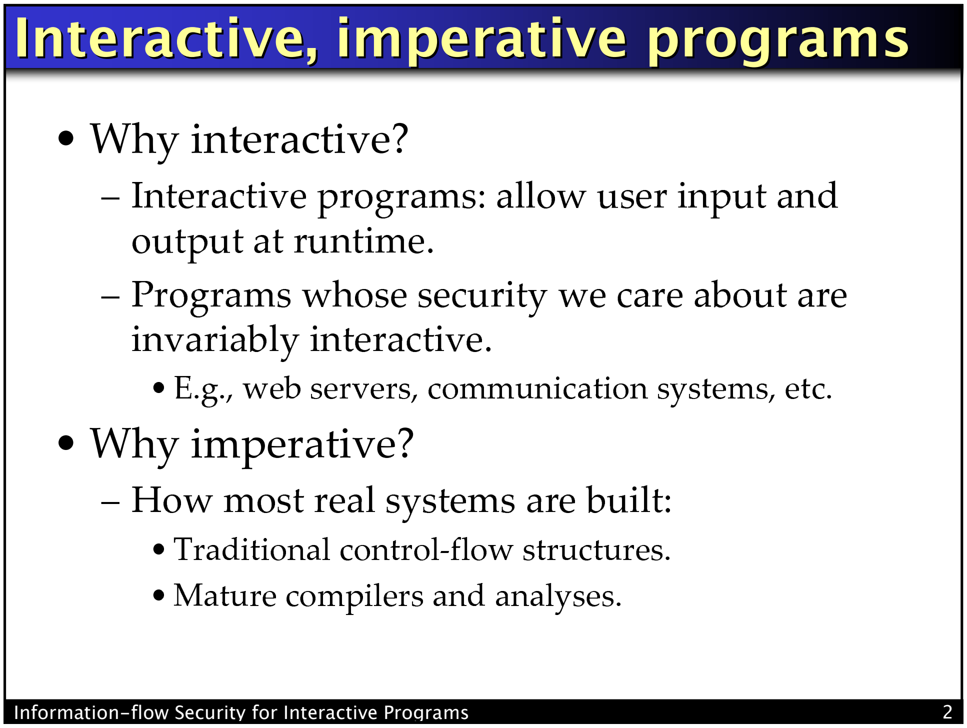
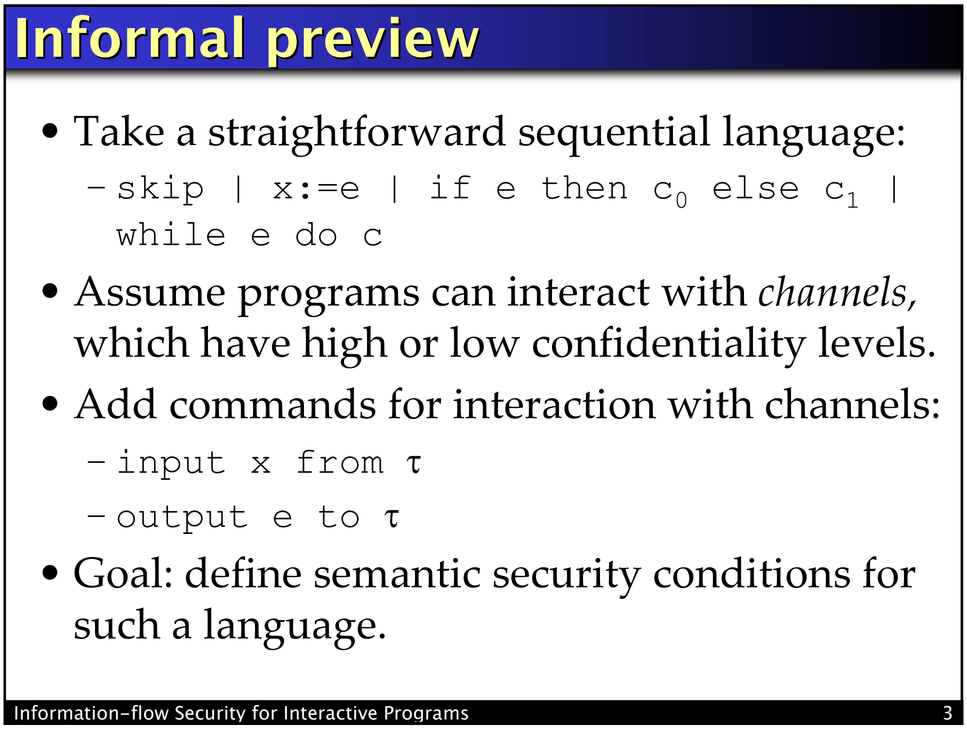
Cornell University

Computer Security Foundations Workshop
July 6, 2006



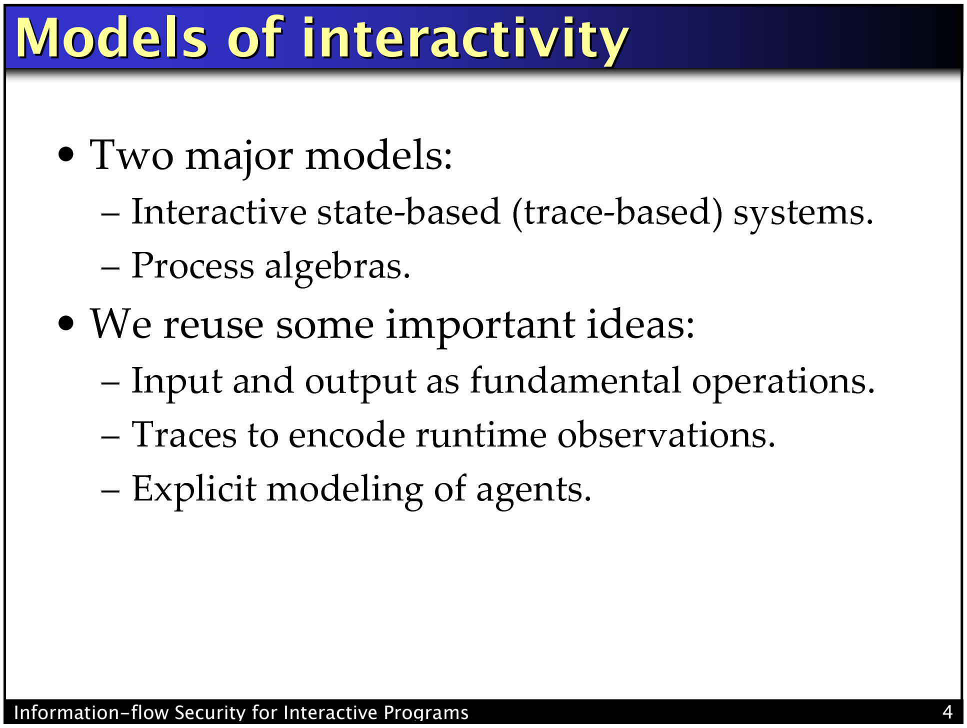
Interactive, imperative programs

- Why interactive?
  - Interactive programs: allow user input and output at runtime.
  - Programs whose security we care about are invariably interactive.
    - E.g., web servers, communication systems, etc.
- Why imperative?
  - How most real systems are built:
    - Traditional control-flow structures.
    - Mature compilers and analyses.



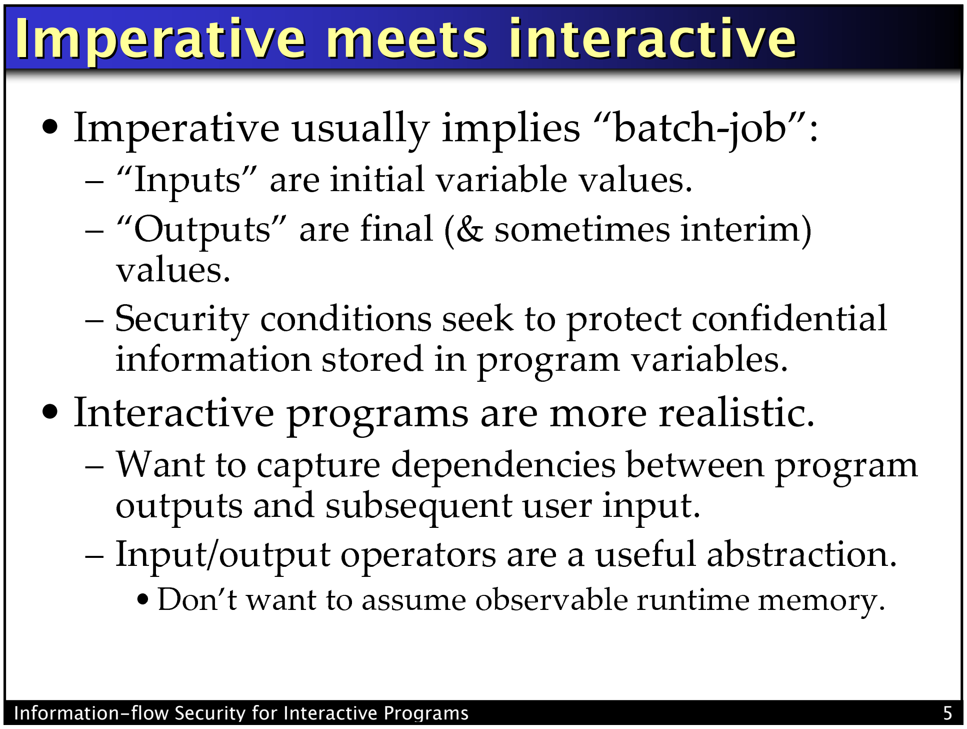
Informal preview

- Take a straightforward sequential language:
  - skip | x:=e | if e then c_0 else c_1 | while e do c
- Assume programs can interact with *channels,* which have high or low confidentiality levels.
- Add commands for interaction with channels:
  - input x from τ
  - output e to τ
- Goal: define semantic security conditions for such a language.



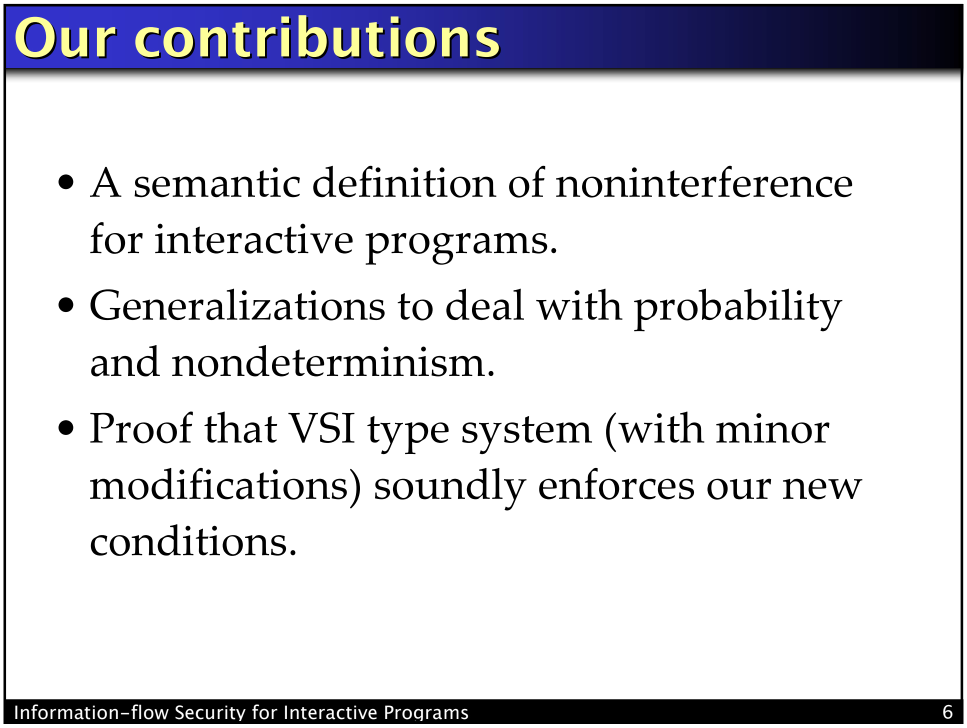
Models of interactivity

- Two major models:
  - Interactive state-based (trace-based) systems.
  - Process algebras.
- We reuse some important ideas:
  - Input and output as fundamental operations.
  - Traces to encode runtime observations.
  - Explicit modeling of agents.



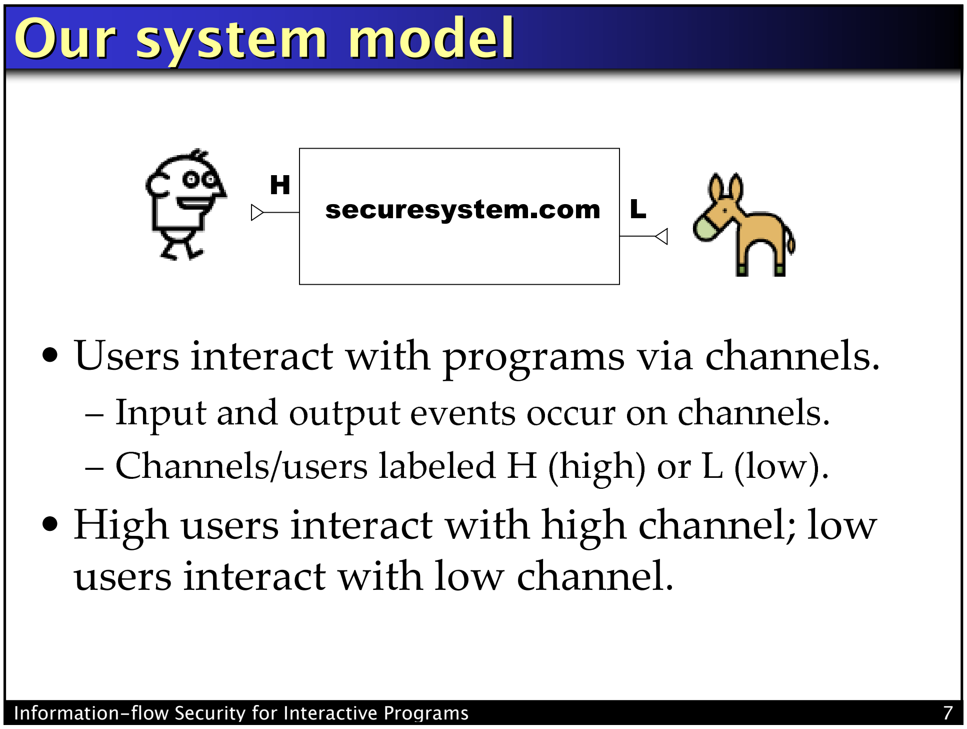
Imperative meets interactive

- Imperative usually implies "batch-job":
  - "Inputs" are initial variable values.
  - "Outputs" are final (& sometimes interim) values.
  - Security conditions seek to protect confidential information stored in program variables.
- Interactive programs are more realistic.
  - Want to capture dependencies between program outputs and subsequent user input.
  - Input/output operators are a useful abstraction.
    - Don't want to assume observable runtime memory.



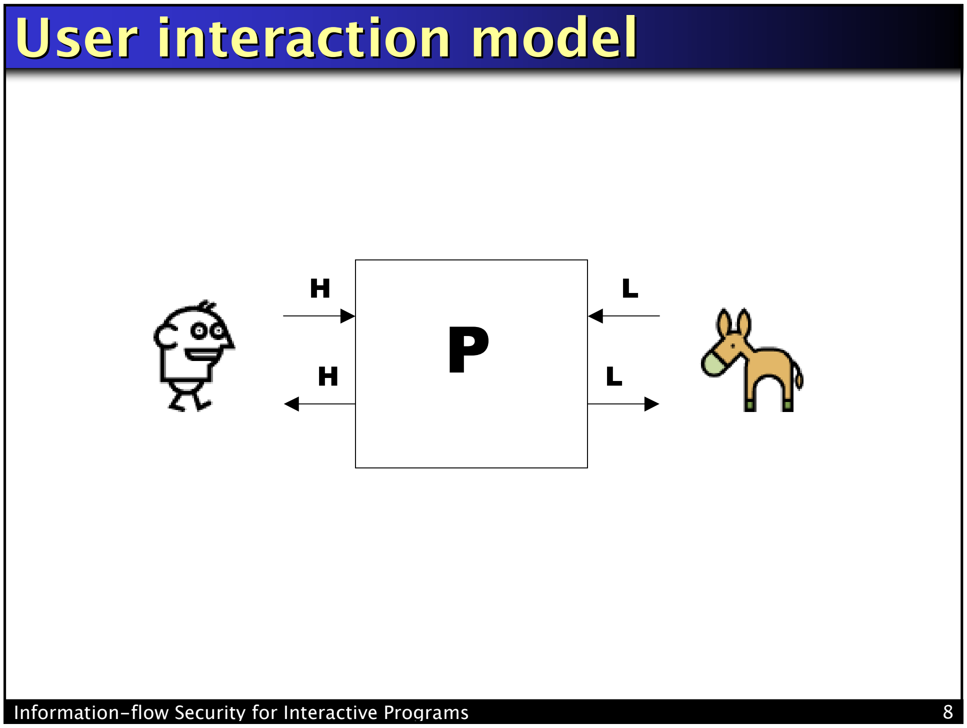
Our contributions

- A semantic definition of noninterference for interactive programs.
- Generalizations to deal with probability and nondeterminism.
- Proof that VSI type system (with minor modifications) soundly enforces our new conditions.

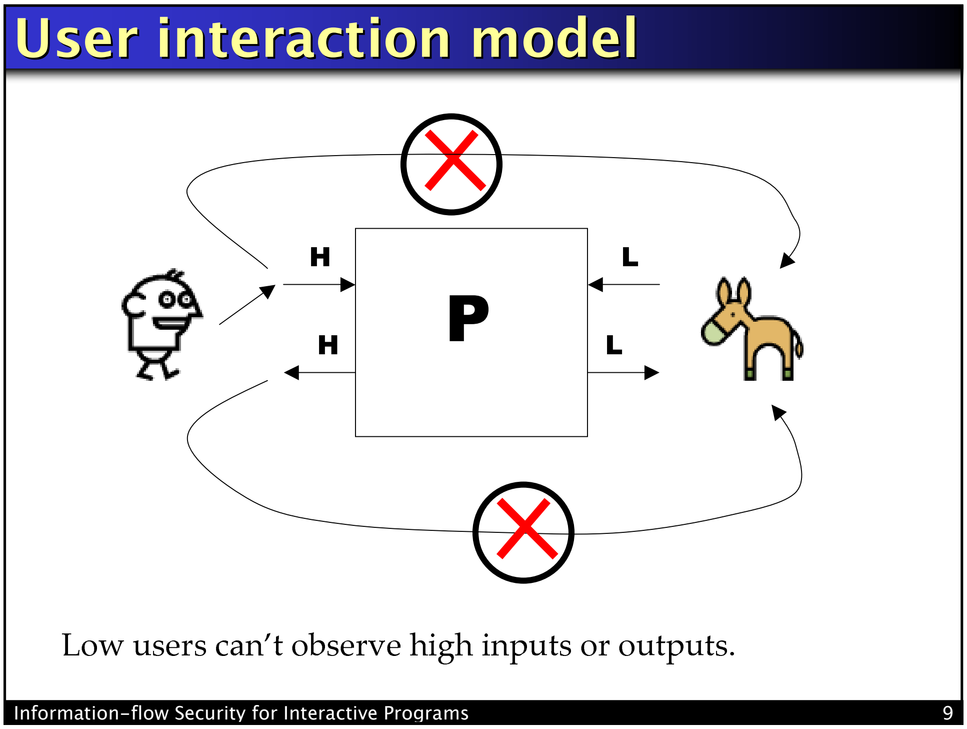


Our system model

- Users interact with programs via channels.
  - Input and output events occur on channels.
  - Channels/users labeled H (high) or L (low).
- High users interact with high channel; low users interact with low channel.



User interaction model



User interaction model

Low users can’t observe high inputs or outputs.

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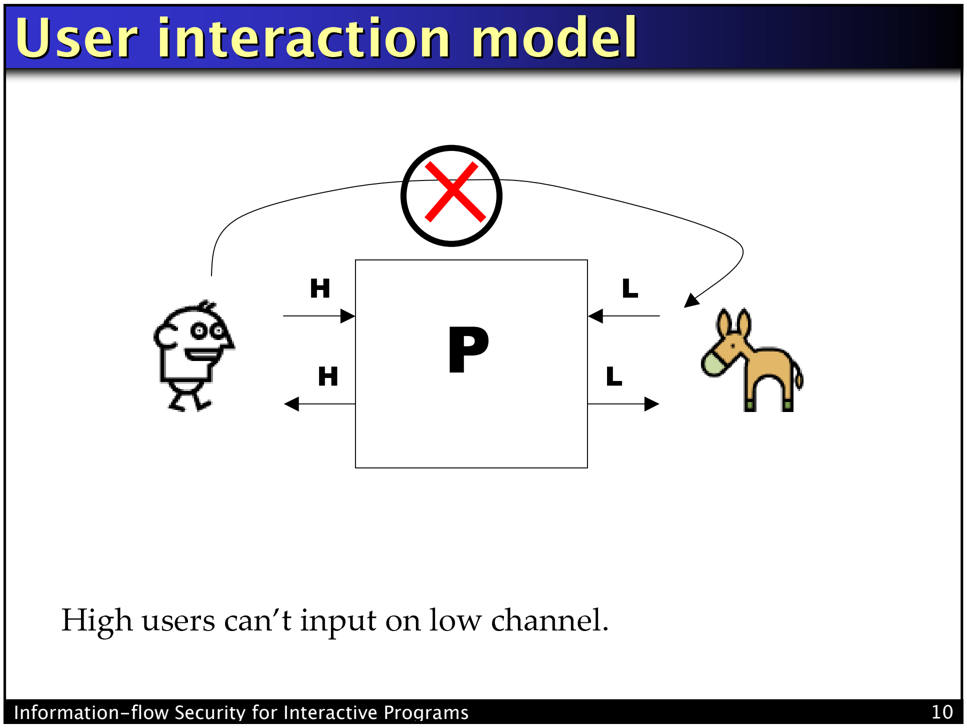

User interaction model

High users can’t input on low channel.

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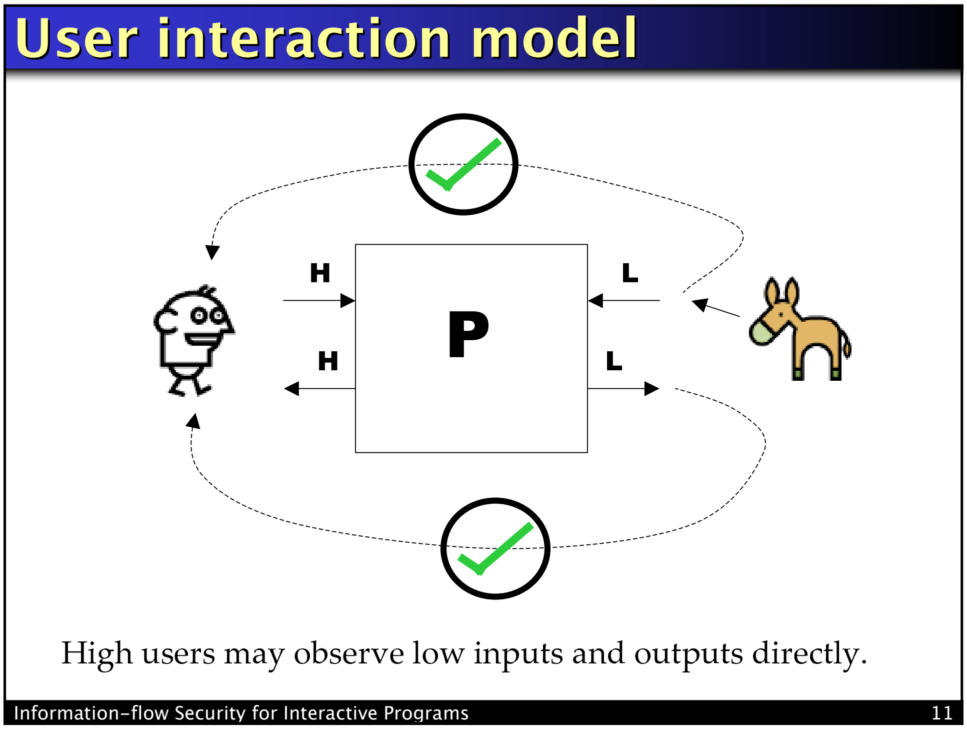
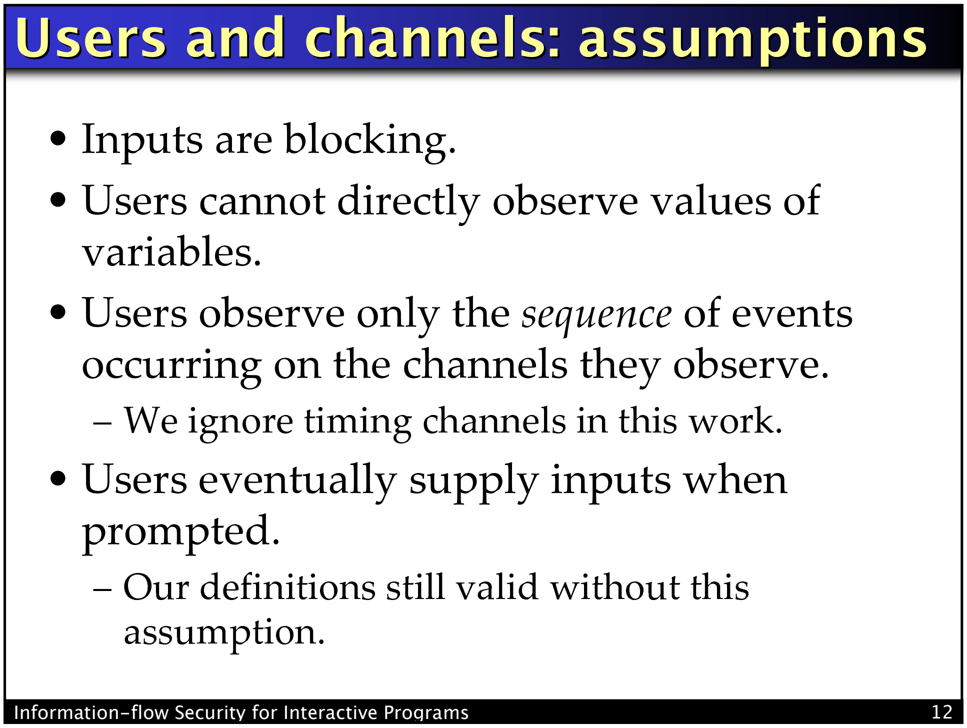


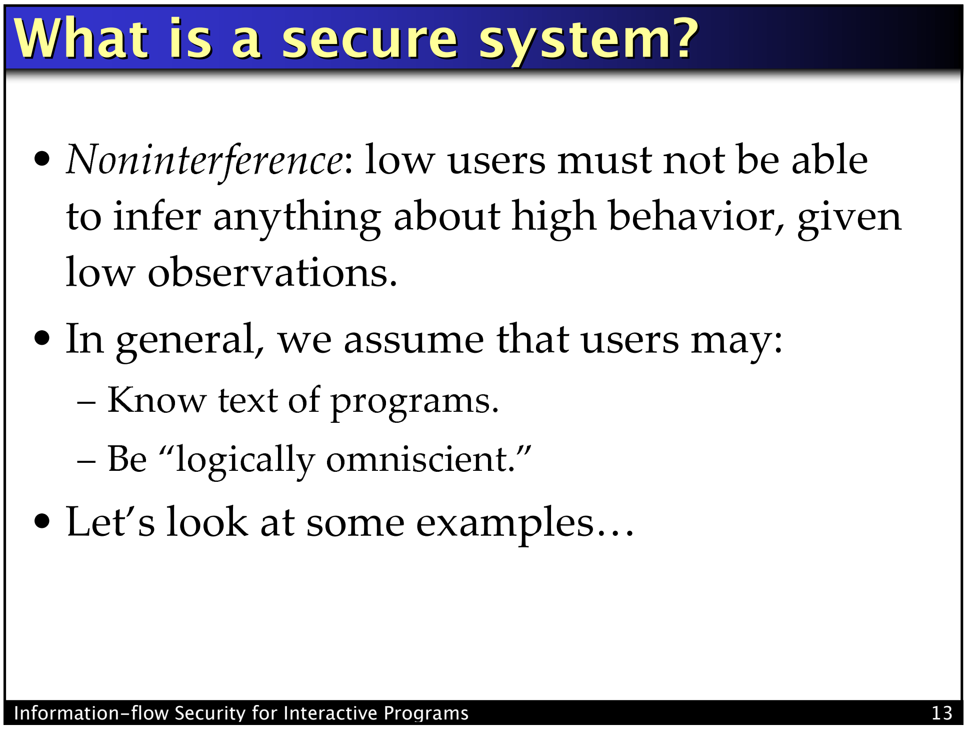
User interaction model

High users may observe low inputs and outputs directly.



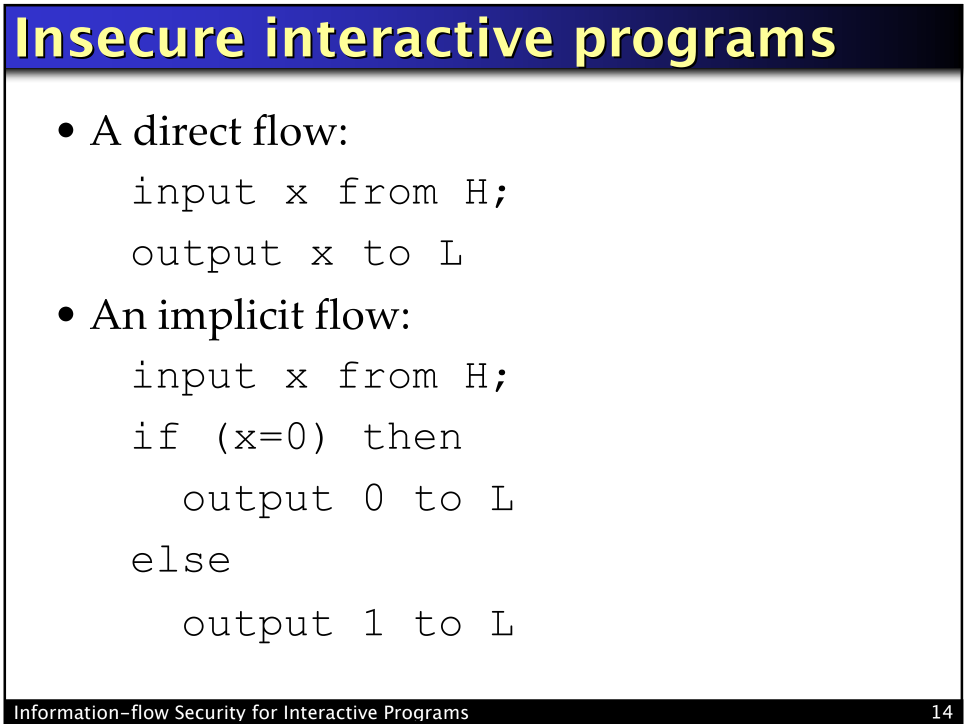
Users and channels: assumptions

- Inputs are blocking.
- Users cannot directly observe values of variables.
- Users observe only the *sequence* of events occurring on the channels they observe.
  - We ignore timing channels in this work.
- Users eventually supply inputs when prompted.
  - Our definitions still valid without this assumption.



What is a secure system?

- *Noninterference*: low users must not be able to infer anything about high behavior, given low observations.
- In general, we assume that users may:
  - Know text of programs.
  - Be “logically omniscient.”
- Let’s look at some examples…



Insecure interactive programs

- A direct flow:

```
input x from H;
output x to L
```

- An implicit flow:

```
input x from H;
if (x=0) then
  output 0 to L
else
  output 1 to L
```

Secure interactive programs

- Programs with no high inputs are secure:

```
    output x to L
```

- Care about high inputs, not contents of memory.
- If programs run multiple times with same memory, can:
  - Require programs to “zero out” memory before each execution.
  - Model program sequence as a single program.

Secure interactive programs

- One-time pad encryption is secure:

```
  while (true) do
    x:=0 [0.5] x:=1;
    input y from H;
    output (x XOR y) to L
```

One-time pad 2.0

- What if we tell high users the one-time pad?

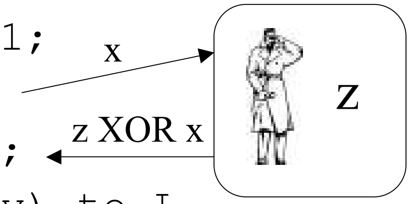
```
while (true) do
   x:=0 [0.5] x:=1;
   output x to H;
   input y from H;
   output (x XOR y) to L
```

- Is this program still secure?
  - Note that low user still can’t infer value of y.

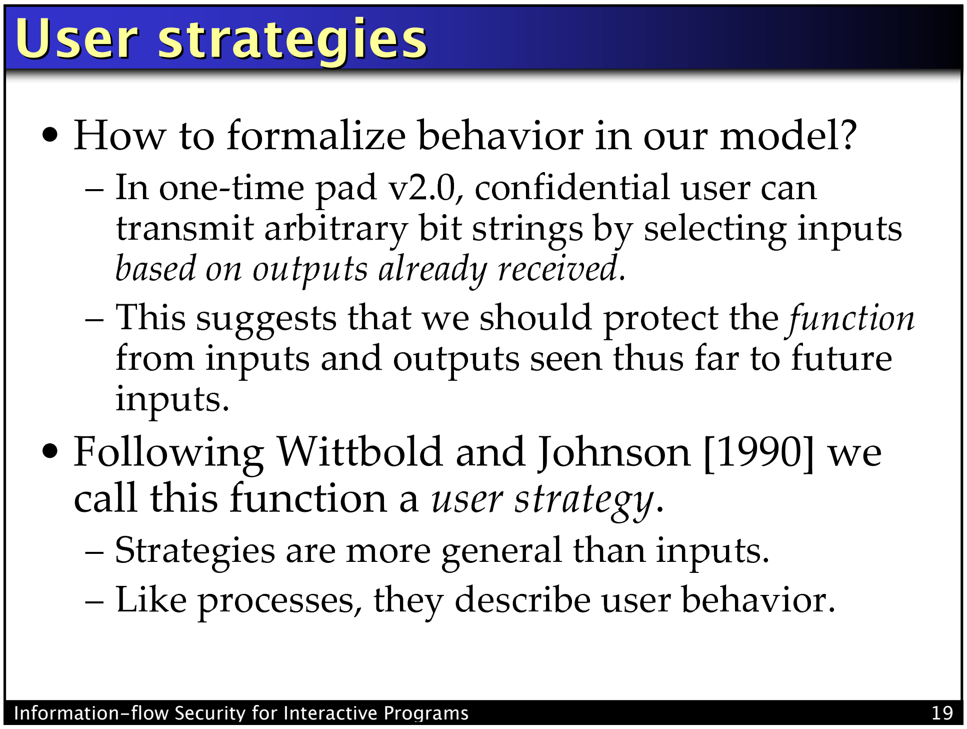
Why v2.0 isn’t secure

- Suppose a high user wants to transmit bit z:

```
while (true) do
   x:=0 [0.5] x:=1;
   output x to H;
   input y from H;
   output (x XOR y) to L
```

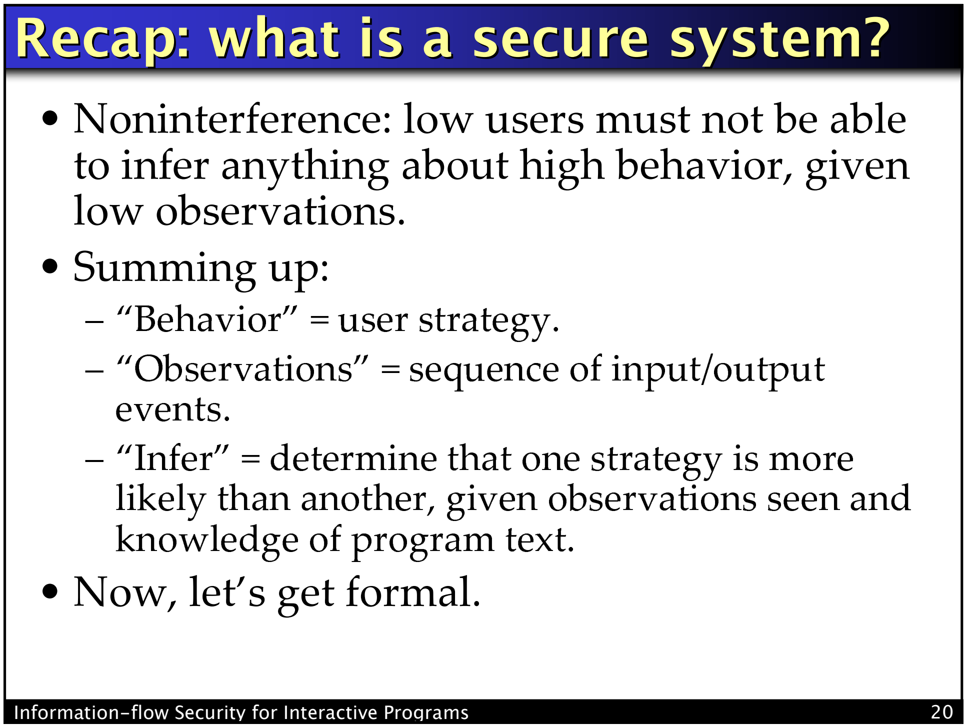


- High user can transmit value z directly.
  - Even though value of y remains secret.
- Thus low users can learn about behavior of high users.



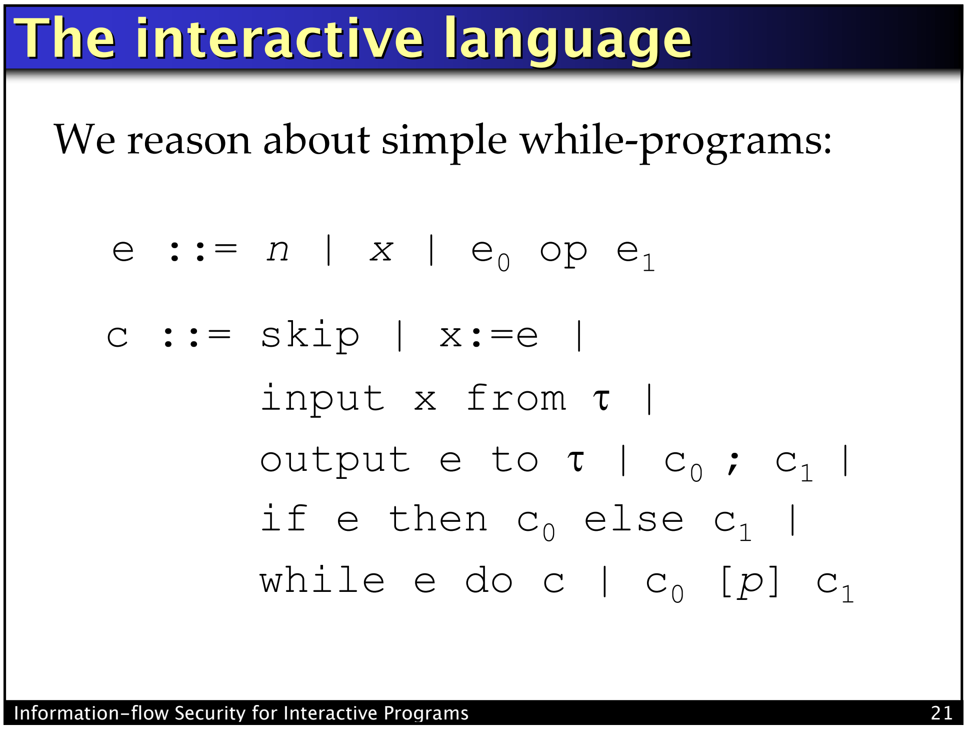
User strategies

- How to formalize behavior in our model?
  - In one-time pad v2.0, confidential user can transmit arbitrary bit strings by selecting inputs *based on outputs already received.*
  - This suggests that we should protect the *function* from inputs and outputs seen thus far to future inputs.
- Following Wittbold and Johnson [1990] we call this function a *user strategy*.
  - Strategies are more general than inputs.
  - Like processes, they describe user behavior.



Recap: what is a secure system?

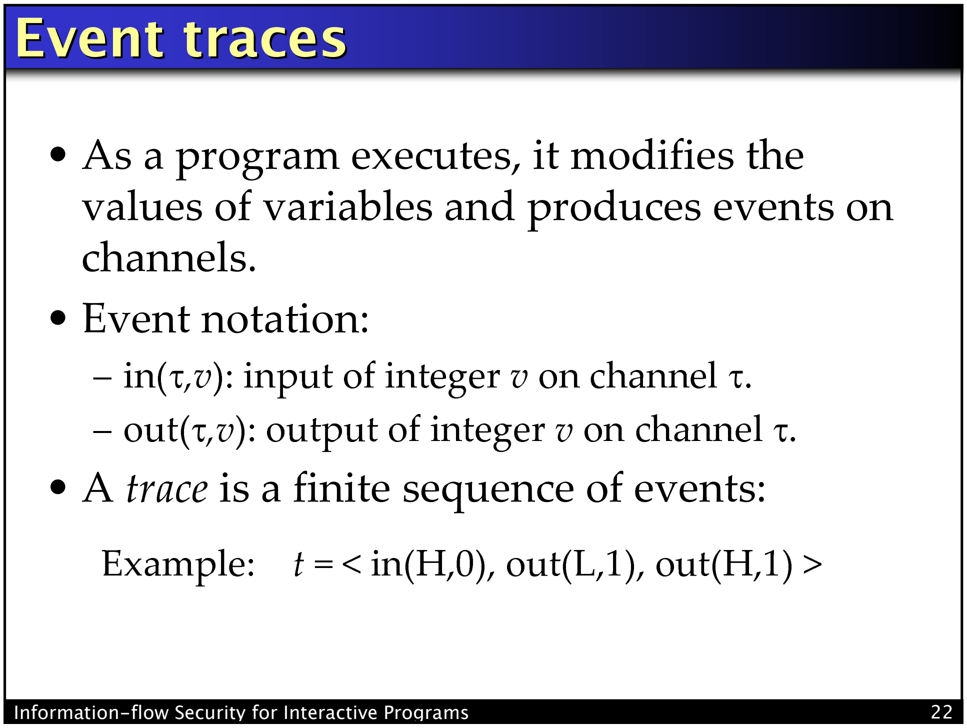
- Noninterference: low users must not be able to infer anything about high behavior, given low observations.
- Summing up:
  - "Behavior" = user strategy.
  - "Observations" = sequence of input/output events.
  - "Infer" = determine that one strategy is more likely than another, given observations seen and knowledge of program text.
- Now, let's get formal.



The interactive language

We reason about simple while-programs:

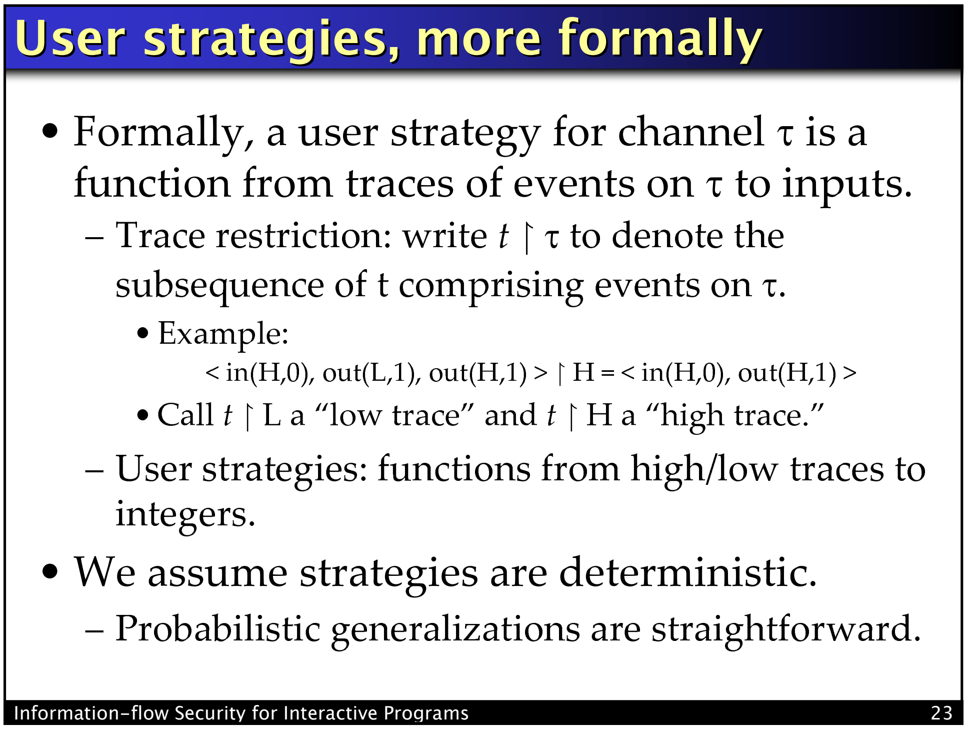
```
e ::= n | x | e₀ op e₁

c ::= skip | x:=e |
      input x from τ |
      output e to τ | c₀ ; c₁ |
      if e then c₀ else c₁ |
      while e do c | c₀ [p] c₁
```



Event traces

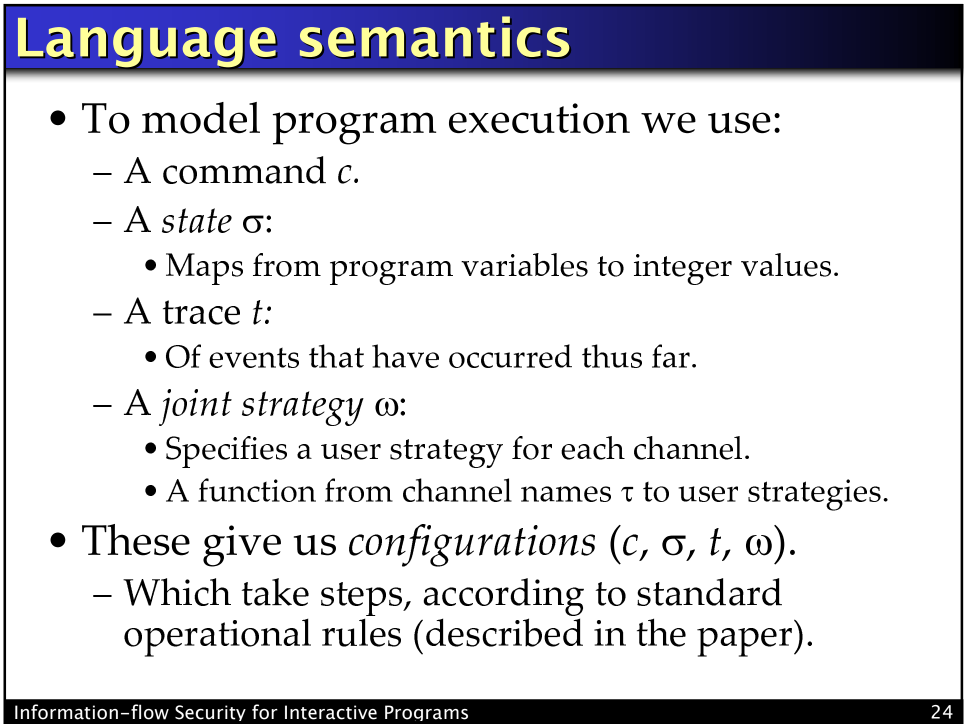
- As a program executes, it modifies the values of variables and produces events on channels.
- Event notation:
  - in(τ,v): input of integer v on channel τ.
  - out(τ,v): output of integer v on channel τ.
- A *trace* is a finite sequence of events:

  Example: t = < in(H,0), out(L,1), out(H,1) >



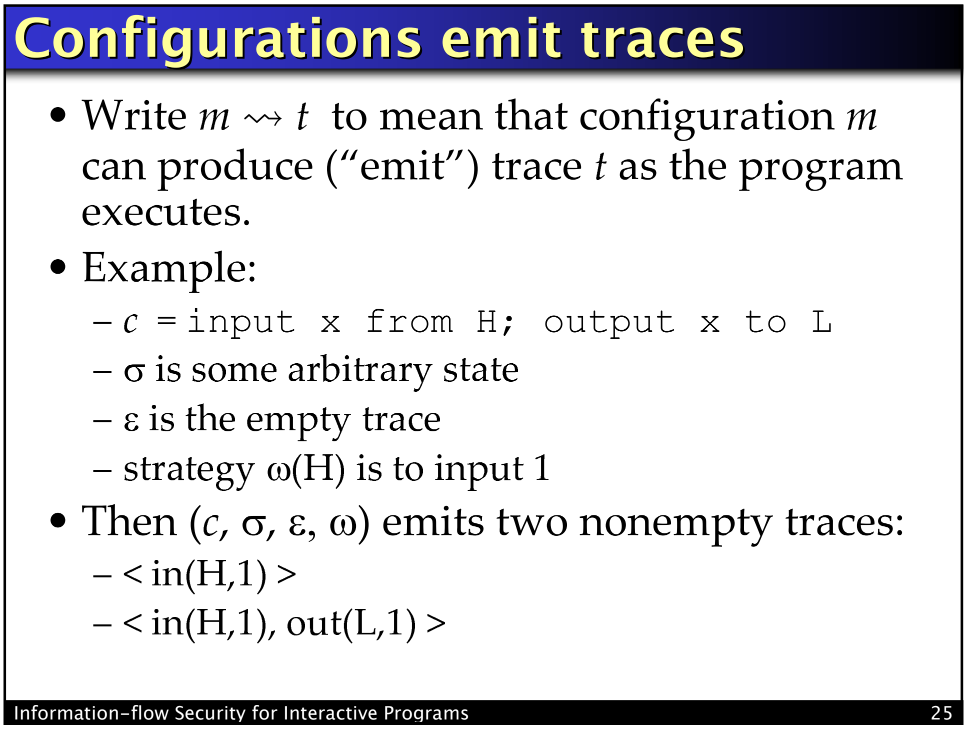
User strategies, more formally

- Formally, a user strategy for channel τ is a function from traces of events on τ to inputs.
  - Trace restriction: write $t \upharpoonright \tau$ to denote the subsequence of t comprising events on τ.
    - Example:
      $<$ in(H,0), out(L,1), out(H,1) $> \upharpoonright$ H = $<$ in(H,0), out(H,1) $>$
    - Call $t \upharpoonright$ L a “low trace” and $t \upharpoonright$ H a “high trace.”
  - User strategies: functions from high/low traces to integers.
- We assume strategies are deterministic.
  - Probabilistic generalizations are straightforward.



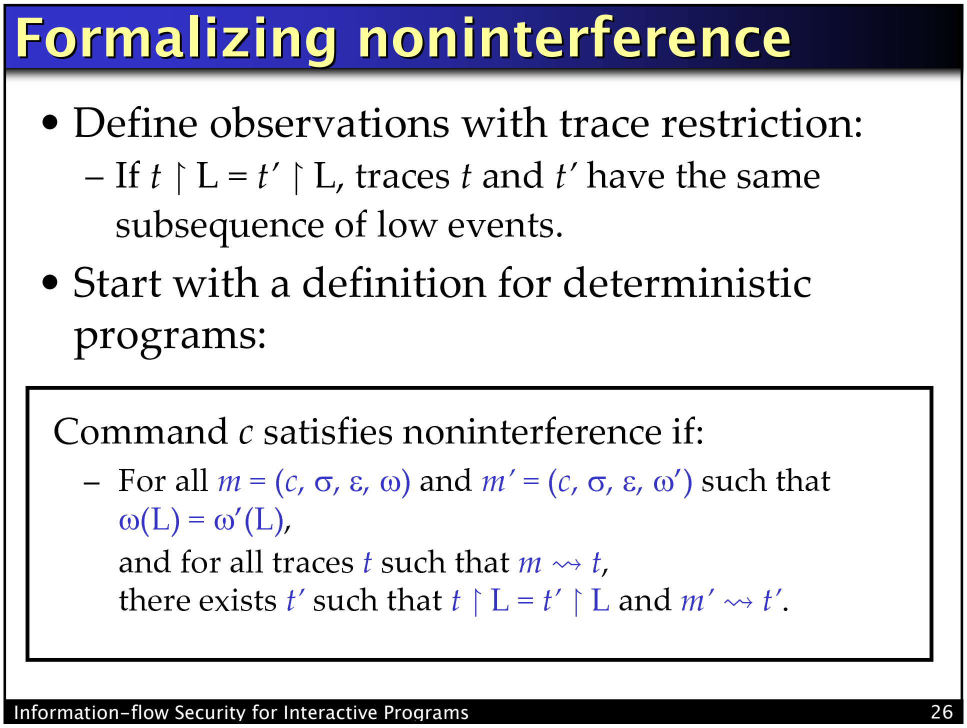
Language semantics

- To model program execution we use:
  - A command *c*.
  - A *state* σ:
    - Maps from program variables to integer values.
  - A trace *t:*
    - Of events that have occurred thus far.
  - A *joint strategy* ω:
    - Specifies a user strategy for each channel.
    - A function from channel names τ to user strategies.
- These give us *configurations* (c, σ, t, ω).
  - Which take steps, according to standard operational rules (described in the paper).



Configurations emit traces

- Write $m \rightsquigarrow t$ to mean that configuration m can produce (“emit”) trace t as the program executes.
- Example:
  - c = `input x from H; output x to L`
  - σ is some arbitrary state
  - ε is the empty trace
  - strategy $\omega(H)$ is to input 1
- Then $(c, \sigma, \varepsilon, \omega)$ emits two nonempty traces:
  - < in(H,1) >
  - < in(H,1), out(L,1) >

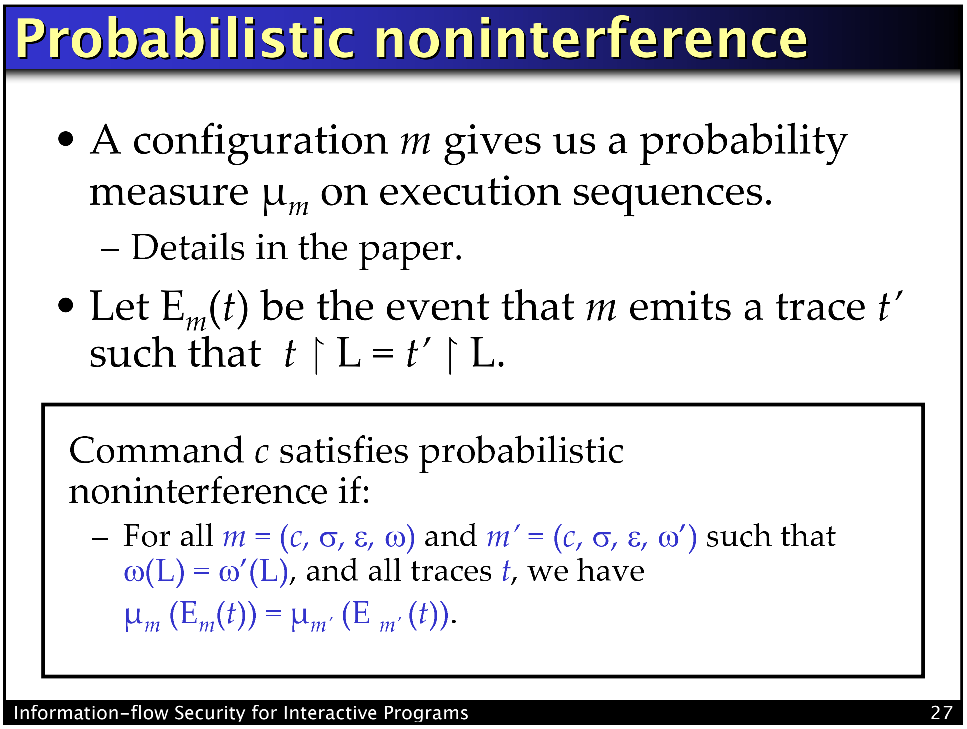


Formalizing noninterference

- Define observations with trace restriction:
  - If $t \upharpoonright L = t' \upharpoonright L$, traces t and t' have the same subsequence of low events.
- Start with a definition for deterministic programs:

Command c satisfies noninterference if:

- For all $m = (c, \sigma, \varepsilon, \omega)$ and $m' = (c, \sigma, \varepsilon, \omega')$ such that $\omega(L) = \omega'(L)$,
  and for all traces t such that $m \rightsquigarrow t$,
  there exists t' such that $t \upharpoonright L = t' \upharpoonright L$ and $m' \rightsquigarrow t'$.



Probabilistic noninterference

- A configuration m gives us a probability measure μ_m on execution sequences.
  - Details in the paper.
- Let $E_m(t)$ be the event that m emits a trace t' such that $t \upharpoonright L = t' \upharpoonright L$.

Command c satisfies probabilistic noninterference if:

- For all $m = (c, \sigma, \varepsilon, \omega)$ and $m' = (c, \sigma, \varepsilon, \omega')$ such that $\omega(L) = \omega'(L)$, and all traces t, we have $\mu_m(E_m(t)) = \mu_{m'}(E_{m'}(t))$.

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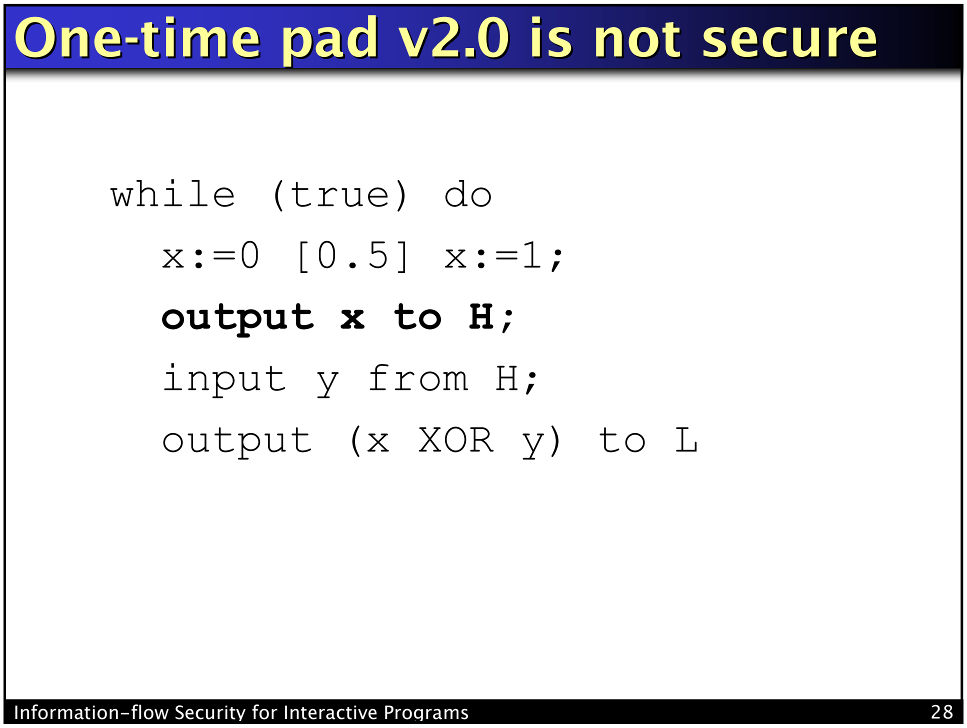

One-time pad v2.0 is not secure

```
while (true) do
  x:=0 [0.5] x:=1;
  output x to H;
  input y from H;
  output (x XOR y) to L
```

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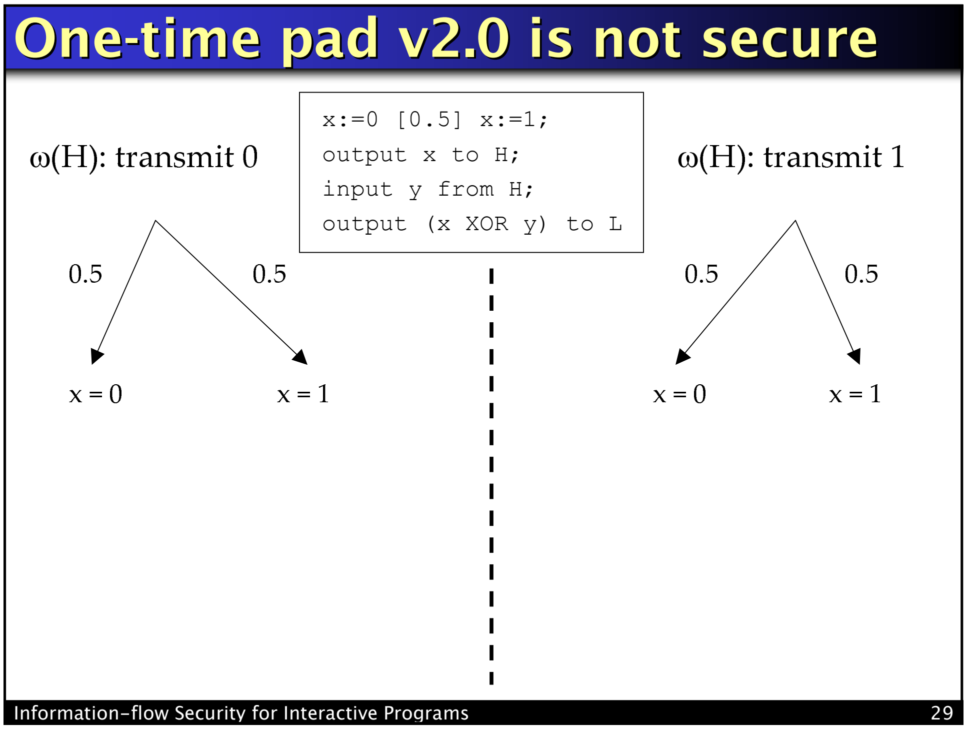

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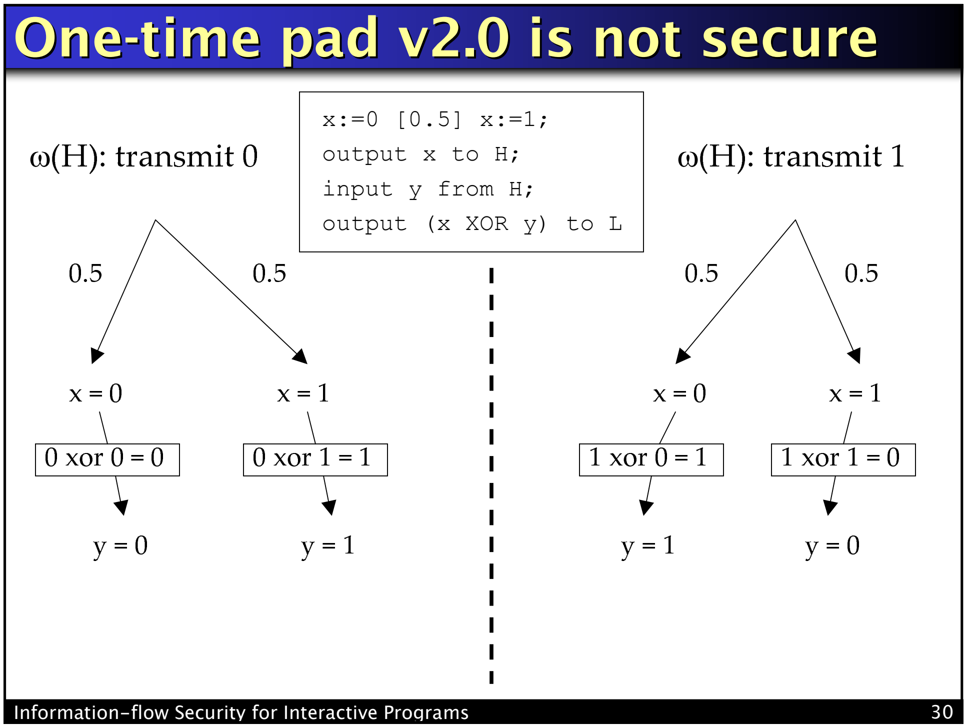

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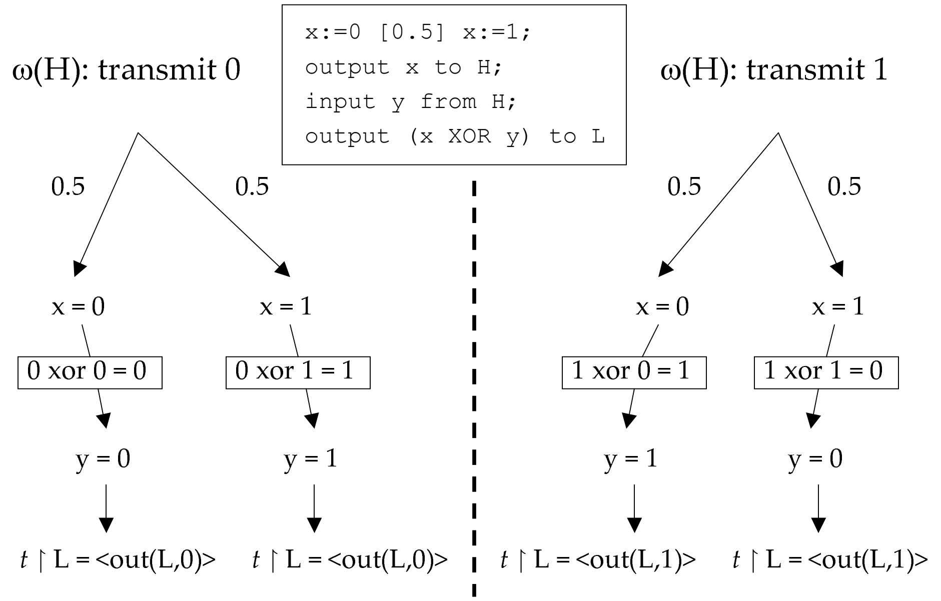
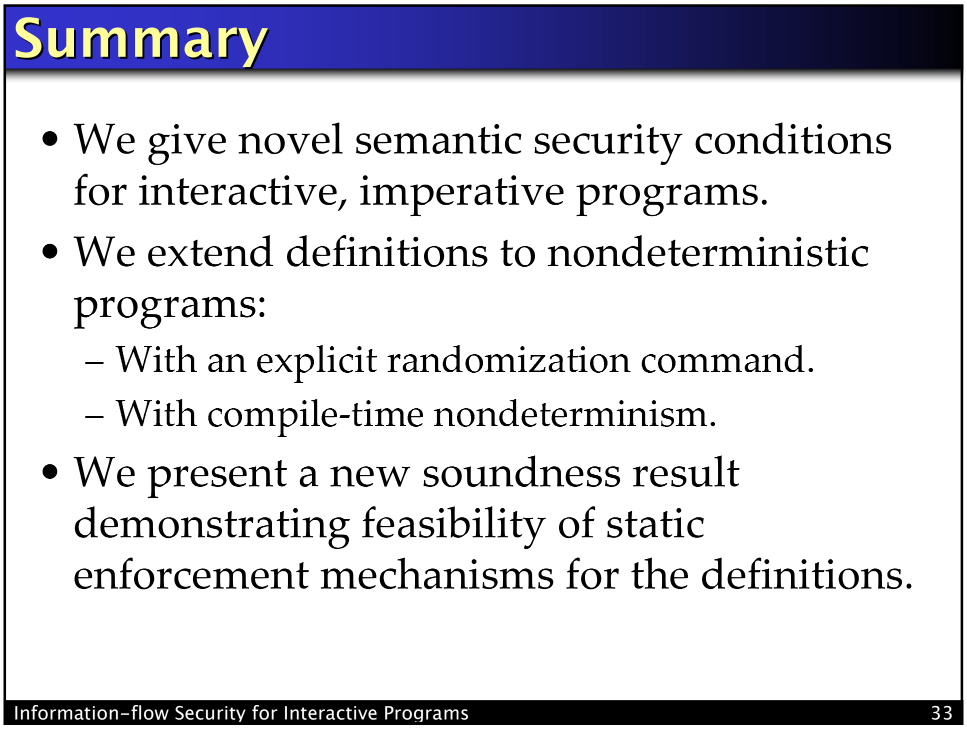


```
x:=0 [0.5] x:=1;
output x to H;
input y from H;
output (x XOR y) to L
```

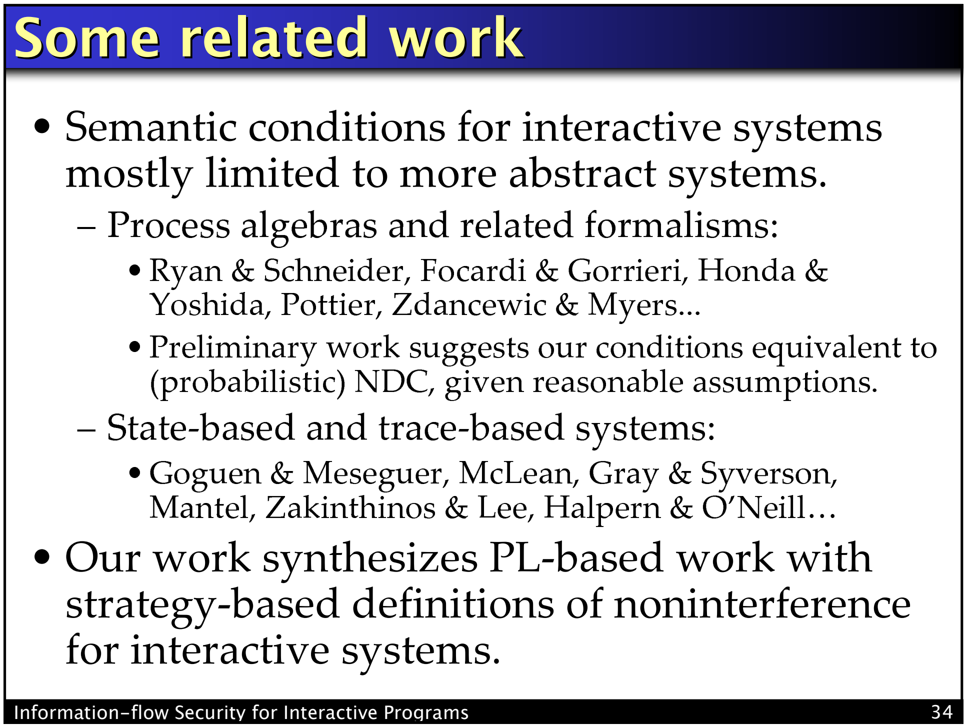
What I didn’t tell you about

- We also handle nondeterministic choice.
  - Like probabilistic choice, but no numbers.
    - Models underspecified behavior like schedulers.
  - *Noninterference under refinement* rules out *refinement attacks* in programs with “compile-time” nondeterminism.
- We prove a result that a variant of VSI type system soundly enforces new conditions.
  - Including probabilistic noninterference.
  - More precise enforcement mechanisms should apply without much extra work.



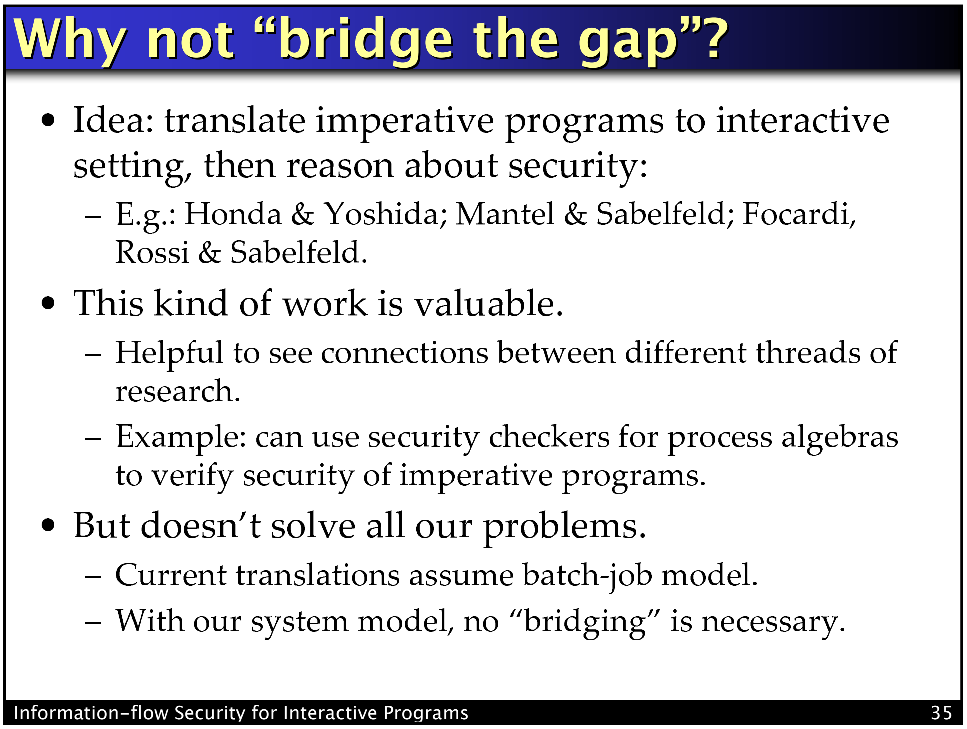
Summary

- We give novel semantic security conditions for interactive, imperative programs.
- We extend definitions to nondeterministic programs:
  - With an explicit randomization command.
  - With compile-time nondeterminism.
- We present a new soundness result demonstrating feasibility of static enforcement mechanisms for the definitions.



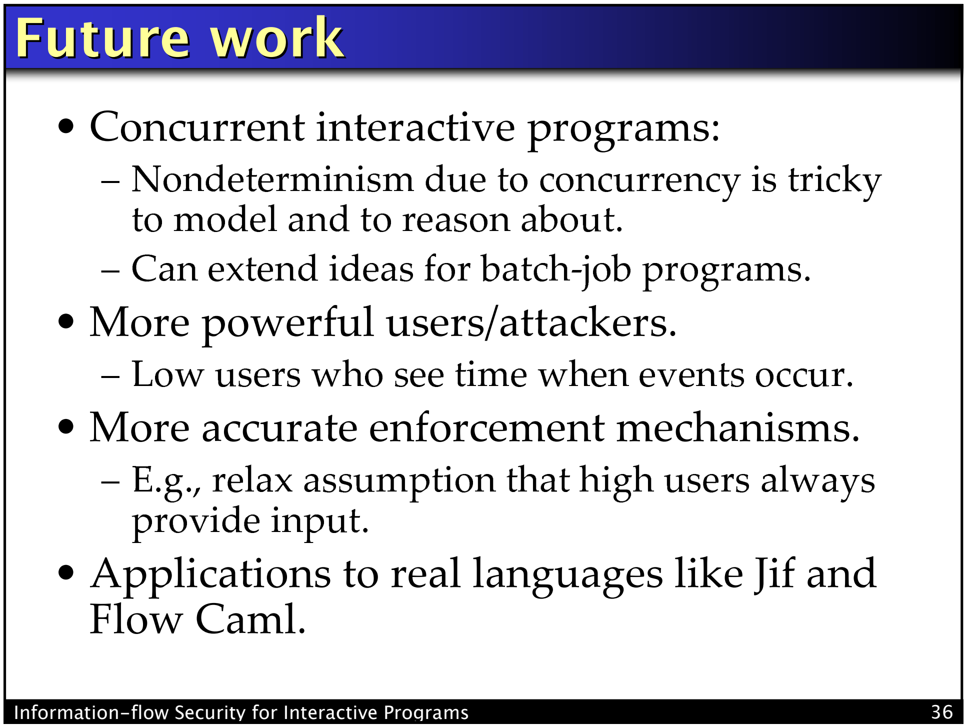
Some related work

- Semantic conditions for interactive systems mostly limited to more abstract systems.
  - Process algebras and related formalisms:
    - Ryan & Schneider, Focardi & Gorrieri, Honda & Yoshida, Pottier, Zdancewic & Myers...
    - Preliminary work suggests our conditions equivalent to (probabilistic) NDC, given reasonable assumptions.
  - State-based and trace-based systems:
    - Goguen & Meseguer, McLean, Gray & Syverson, Mantel, Zakinthinos & Lee, Halpern & O'Neill…
- Our work synthesizes PL-based work with strategy-based definitions of noninterference for interactive systems.



Why not "bridge the gap"?

- Idea: translate imperative programs to interactive setting, then reason about security:
  - E.g.: Honda & Yoshida; Mantel & Sabelfeld; Focardi, Rossi & Sabelfeld.
- This kind of work is valuable.
  - Helpful to see connections between different threads of research.
  - Example: can use security checkers for process algebras to verify security of imperative programs.
- But doesn't solve all our problems.
  - Current translations assume batch-job model.
  - With our system model, no "bridging" is necessary.



Future work

- Concurrent interactive programs:
  - Nondeterminism due to concurrency is tricky to model and to reason about.
  - Can extend ideas for batch-job programs.
- More powerful users/attackers.
  - Low users who see time when events occur.
- More accurate enforcement mechanisms.
  - E.g., relax assumption that high users always provide input.
- Applications to real languages like Jif and Flow Caml.