

# Nondeterminism and Information Flow

ca. 1986-1997

Michael Clarkson

CS 711

10/29/2003

## Limited Chronology

- 1986 – Nondeducibility (ND)
- 1987 – Generalized noninterference (GNI)
- 1988 – Forward correctability (FC)
- 1990 – Restrictiveness (RES), Flow model (FM), Nondeducibility on strategies (NDS)
- 1994 – Separability (SEP)
- 1997 – Perfect security property (PSP)

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## Relative Power

- Depends on exact definitions and assumptions
  - These vary widely, especially for GNI

- Under input totality:

SEP  $\Rightarrow$  PSP  $\Rightarrow$  RES  $\Rightarrow$  FC  $\Rightarrow$  GNI

[Zakinthinos & Lee 97]

- Without input totality:



[Mantel 02]

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## Nondeducibility

[Sutherland 86]

Low-security users should not be able to deduce *with certainty* anything about the activities of high-security users

– Cannot rule out any high activities

– S is secure when:

- For all  $l \in l\text{-traces}(S)$ ,  $h \in h\text{-traces}(S)$ ,  $\text{interleavings}(l,h) \subseteq \text{traces}(S)$

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## Nondeducibility

Can also formulate in terms of statistical independence:

$$\Pr(l) > 0 \text{ and } \Pr(h) > 0 \Rightarrow \Pr(h | l) > 0$$

=

$$\Pr(l) > 0 \text{ and } \Pr(h) > 0 \Rightarrow \Pr(l | h) > 0$$

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## Nondeducibility

Problems with nondeducibility:

– Disallows some safe flows

- e.g., auditing: flows from L to H [McLean 90]

– High events can still affect low events

[McCullough 87]

– Not preserved under feedback/composition

- Based on single traces, not sets

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# Generalized Noninterference

[McCullough 87]

- Changes in high level input events do not cause changes in low level events
  - Fixes bug in ND
  - If all inputs happen before all outputs, generalizes:
 
$$\sigma_1 \approx_L \sigma_2 \Rightarrow \llbracket S \rrbracket \sigma_1 \approx_L \llbracket S \rrbracket \sigma_2$$
    - Domain of  $\llbracket S \rrbracket$  becomes sets of states
    - $\approx_L$  becomes low-view set equality

# Generalized Noninterference

If inputs and outputs are interleaved:

For all  $t \in \text{traces}(S)$ ,  $s = \text{change-high-input}(t1)$ ,  
 There exists  $t' \in \text{traces}(S)$  s.t.  
 $t = uw, s = uw', t' = uw''$  &  $w' \approx_{\neg HO} w''$

# Generalized Noninterference

- Not preserved under composition:
  - Machine A:
    - on receive H input: echo to H output
    - on receive "reset" (L input):
      - echo to L output
      - cancel all pending H outputs
      - if there were none, nondeterministically choose
        - » output "nothing to reset"
        - » no output
  - Machine B:
    - Same as A except no echo of "reset" to L output

# Generalized Noninterference

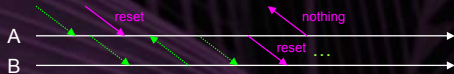
- A and B satisfy GNI
  - Because of ND choice, can't tell whether change in H inputs has caused any change in L outputs

```

- Machine A:
  • on receive "reset":
    - echo to L output
    - cancel all pending H outputs
    - if there were none, nondeterministically choose
      » output "nothing to reset"
      » no output
- Machine B:
  • Same as A except no echo of "reset" to L output
    
```

# Generalized Noninterference

- Composition of A and B doesn't satisfy GNI



Odd number of H inputs makes it impossible for both machines to output "nothing"

```

- Machine A:
  • on receive "reset":
    - echo to L output
    - cancel all pending H outputs
    - if there were none, ND choose
      » output "nothing to reset"
      » no output
  • on receive "nothing", echo to L output
- Machine B:
  • Same as A except no echo of "reset" to L output
    
```

# Composition Paradox

- Individual systems secure; composition insecure
- Composition of safety, liveness properties well-understood [Alpern & Schneider 85]
- Why not security?
  - Many security properties outside of safety/liveness domain [McLean 94]

## Composition Paradox

- Can we develop a theory of composition?
  - [McLean 94], [Zakinthinos & Lee 97], [Mantel 00, 02]
- Before these, there were various *ad hoc* compositional properties
- Not the only paradox...

## Refinement Paradox

- A ND program is secure, but a refinement of it is not:

```

1 := h [] 0 [] 1; // secure
1 := h [] 0;     // insecure
    
```

- Recent work [Zdancewic & Myers 03] shows how to solve this problem
- More on this later in the course

## Restrictiveness [McCullough 90]

- Fix GNI so that it is composable
- Recall GNI is:
  - For all  $t \in \text{traces}(S)$ ,  $s = \text{change-high-input}(t1)$ ,  
There exists  $t' \in \text{traces}(S)$  s.t.  
 $t = uw, s = uw', t' = uw'' \ \& \ w' \approx_{\text{HO}} w''$
- Changing H inputs may require introducing new H outputs
- After composition, new outputs from A become secret inputs to B
- Result: cascade of changes

## Restrictiveness

- McCullough's solution:
  - Restrict exchange of messages
  - Results in composability

For all $t \in \text{traces}(S)$ , $s = \text{change-high-input}(t1)$ , There exists $t' \in \text{traces}(S)$ s.t. $t = uw, s = uw', t' = uw'' \ \& \ w' \approx_{\text{HO}} w''$	} GNI
$\ \& \ w = xy, w' = x'y', w'' = x'y''$ $\ \& \ x, x'$ contain only inputs	

} RES

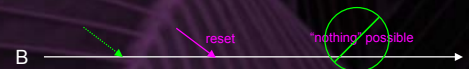
## Restrictiveness

- Reject systems that require:
  - Insertion of new H output
  - Before/during the sequence of inputs after 1<sup>st</sup> change in H input
- Machine B from GNI was not restrictive:



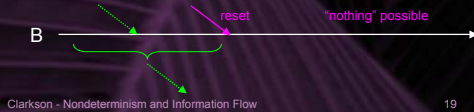
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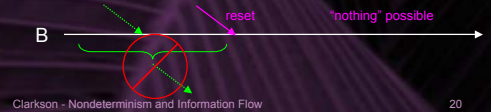
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## Flow Model [McLean 90]

- Recall another bug in ND:
  - ND disallows some safe flows
    - e.g., auditing: flows from L to H
  - Results from symmetry of independence:
 
$$\Pr(h | l) = \Pr(h) \equiv \Pr(l | h) = \Pr(l)$$

## Flow Model

- Solution: break the symmetry using time
  - Not ok for  $h_t$  to affect  $l_{t+1}$
  - But ok for  $l_t$  to affect  $h_{t+1}$
- “Affect”: statistical and causal dependency

## Flow Model

- FM requires that  $l_t$  be independent of  $h_{0..t-1}$ :
 
$$\Pr(l_t | l_{0..t-1} \ \& \ h_{0..t-1}) = \Pr(l_t | l_{0..t-1})$$
- High events can be correlated with low events if caused by previous low event

## Flow Model

- GNI and its extensions ignore causal dependencies
  - Overly restrictive
- FM allows more useful programs than GNI, ND, etc.
- But still ensures high level of security
- FM later extended to quantitative information flow [Gray 91]

## Nondeducibility on Strategies

[Wittbold and Johnson 90]

- Recall problem with ND
  - Nondeducible on a single run
  - Leaks information every  $n$  runs
  - Strategy exists to leak information
- Can require system to be nondeducible on any strategy
  - Formulated using information theory
  - System is NDS iff there exist no noiseless communication channels

## Separability

[McLean 94]

- Absolutely no possibilistic information flow
- Like running the system as two separate, non-communicating processes
  - One process for each security level
- Few (useful) systems can satisfy this property

## PSP

[Zakinthinos & Lee 97]

- Weaken SEP to allow high outputs to depend on low events
  - But all high inputs still possible
- Flow occurs when some high trace is not possible
  - Construction guarantees that low user can't tell what that trace is
- Provably weakest such property
- Also composable

## Conclusion

- Not too hard to generalize information flow to nondeterministic systems
- Hard to find balance between security and utility



- Coming up: restricting, quantifying nondeterminism