Secure information flow for concurrent processes

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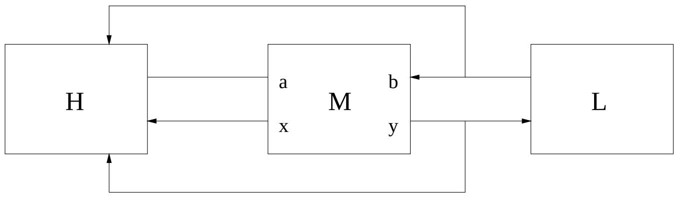
Problem

Untrusted H (post-issuance download on multi-app smartcard, off-the shelf component, . . . possibly Trojan Horse) accesses confidential data.

Prevent H from sending data to L (e. g. Internet).

M (operating system (TCB), browser, . . .) should prevent information flow from H to L.



Subtlety

Covert channels (Butler Lampson 73):

E.g., send information from H through M to L by increased use of common resources at certain times

Dean e.a. 98: covert channels in web browsers

Background

Bell, LaPadula 75 does not treat covert channels.

Thus Noninterference (Goguen, Meseguer 82) for deterministic systems: L cannot distinguish different behaviours of H.

Nondeterministic systems: Nondeducibility-on-Strategies (Wittbold, Johnson 90). Attacks using statistical inference.

Probabilistic: Applied Flow Model (McLean 90, Gray 92), Probabilistic Noninterference (Gray 92).

Nonprobabilistic notions using process algebras (Ryan 90, Focardi/Gorrieri 94, Roscoe/Woodcock/Wulf 94, . . .).

Present work

Simplified verification of probabilistic secure information flow.

Note weakness of Applied Flow Model.

Prove results towards feasible verification of PNI:

- Determinism Theorem
- Compositionality (open in Gray 92),
  using rely/guarantee principle
- relation to Nondeducibility-on-Strategies

Why Probability ?

System M:

- receives high value a.
- with probability 1/2, M outputs a to Low,
- with probability 1/2, M outputs random value to Low.

Then

- M secure in nonprobabilistic models (that allow nondeterminism visible to L),
- covert channel from High to Low using statistical inference.

System Model: Probabilistic Dataflow

probabilistic vs. of I/O systems (Jonsson)

- concurrent probabilistic processes
- transmit data values over unidirectional FIFO channels
- communication asynchronous

Consider systems (security to be examined) and environments

Processes: Systems and Environments

$\mathcal{E}_C$ set of events $o : C \to \mathcal{D}$ (C channels, $\mathcal{D}$ data values)

For system M (I, O input, output channels), environment E:
- $\mathcal{E}^M := (\mathcal{E}_O \times \mathcal{E}_I)^*$ (system histories)
- $\mathcal{E}^E := \mathcal{E}_O \times (\mathcal{E}_I \times \mathcal{E}_O)^*$ (environment histories)

System: $M = (I, O, P_M)$, $P_M : \mathcal{E}_O \times \mathcal{E}^M \to [0, 1]$

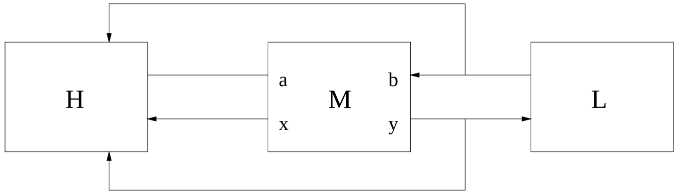
Environment: $E = (O, I, P_E)$, $P_E : \mathcal{E}_I \times \mathcal{E}^E \to [0, 1]$

For each w, $\sum_o P(o, w) = 1$.
$P(o \mid w) \stackrel{\text{def}}{=} P(o, w)$ (probability of value o after history w).

Processes: High and Low

Environment: independent components H (high) and L (low).
H can read low outputs.

$M = (I, O, P_M((x,y) \mid w))$ $(w \in \mathcal{E}^M)$,
$L = (O_l, I_l, P_L(b \mid w\lfloor_l))$
    ($w\lfloor_l$ restriction of $w \in \mathcal{E}^{H,L}$ to low channels)
$H = (O \cup I_l, I_h, P_H(a \mid w))$ $(w \in \mathcal{E}^{H,L})$.



1) Applied Flow Model

Definition: A system M satisfies Applied Flow Model (AFM) if for all traces w, w' identical wrt. the low input and output, and for all low outputs y,

$$\sum_x P_M((x,y) \mid w) = \sum_x P_M((x,y) \mid w').$$

Simple but too strict (Gray 92).

Applied Flow Model: Subtlety

Worse: against common sense:

System S:

random number generator R outputs r to

- high output of S and to
- delay component D.

D outputs r after one time step at low output of S.

S secure: H has no way of influencing the low output of S.

S does not satisfy AFM.

However, if substitute D by wire (so L gets r earlier), get system that does satisfy AFM ! Unrealistic since L has state.

2) Weak AFM

Definition: A process M fulfils weak AFM
if for all possible traces w and w' that are
identical wrt. the low input and output and the high output,
and all low-level output events y,

$$\sum_x P_M((x,y) \mid w) = \sum_x P_M((x,y) \mid w').$$

Weak AFM: Subtlety

Also too strict:
Let M output $x_1 = 0$ resp. $x_1 = 1$ each with probability 1/2 to H, and $y_1 = 0$ to L.
On input of a_1 (resp. b_1) from H (resp. L) M outputs $x_2 = 0$ to H and y_2 to L:
$x_1 = 0$: $y_2 := a_1$ resp. $\neg a_1$ with probability 1/4 resp. 3/4
$x_1 = 1$: $y_2 := \neg a_1$ resp. a_1 with probability 1/4 resp. 3/4

M secure, because independently of H, L receives 0 and 1 each with probability 1/2.
But M does not satisfy weak AFM:
$P(a_1 \mid (a_1, x_1 = 0)) = 1/4 \neq 3/4 = P(a_1 \mid (\neg a_1, x_1 = 0))$.

Probabilistic Noninterference

Probability of history $w \in \mathcal{E}^M$ by $P^M_{H,L}(\varepsilon) \stackrel{\text{def}}{=} 1$,

$$P^M_{H,L}(w.(x,y).(a,b)) \stackrel{\text{def}}{=}$$
$$P^M_{H,L}(w) \cdot P_M((x,y) \mid w) \cdot P_H(a \mid w.(x,y)) \cdot P_L(b \mid w\downharpoonright_l .y)$$

Probability of low history w_l: $P^l_{H,L}(w_l) \stackrel{\text{def}}{=} \sum_{w : w\downharpoonright_l = w_l} P_{H,L}(w)$

Definition: System M satisfies Probabilistic Noninterference (PNI) if for all H, H', L and low histories w_l

$$P_{H,L}(w_l) = P_{H',L}(w_l).$$

M satisfies PNI $\Rightarrow$ communication channel from H to L has capacity zero (Gray 92).

Deterministic Adversaries suffice

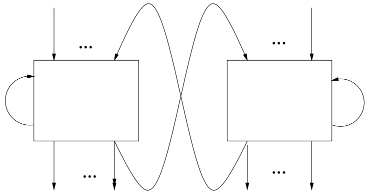
Process (I, O, P) is deterministic if for all w, o have $P(o \mid w) \in \{0, 1\}$.

Determinism Theorem: A system M satisfies Probabilistic Noninterference iff for all deterministic H, H', L and for all low system histories w_l we have

$$P_{H,L}(w_l) = P_{H',L}(w_l).$$

Composition

Define composition $M \otimes N$ of systems M, N with $O_M \cap O_N = \emptyset$:



- $O_{M\otimes N} = O_M \cup O_N$
- $I_{M\otimes N} = I_M \cup I_N \setminus O_{M\otimes N}$

- $P^{M\otimes N}(o \otimes p | v \otimes w) = P^M(o|v) \cdot P^N(p|w)$ for *compatible* v, w

For output events $e : O_M \to \mathcal{D}$, $f : O_N :\to \mathcal{D}$: $e \otimes f \stackrel{\text{def}}{=} (e \cup f)$,

for input events $e : I_M \to \mathcal{D}$, $f : I_N :\to \mathcal{D}$: $e \otimes f \stackrel{\text{def}}{=} (e \cup f) \restriction_{I_{M\otimes N}}$,

for histories v, w: $(v_1, \ldots, v_t) \otimes (w_1, \ldots, w_t) \stackrel{\text{def}}{=} (v_1 \otimes w_1, \ldots, v_t \otimes w_t)$.
Histories v, w are compatible if outputs match with inputs at corresponding channels at following time step.

Compositionality: Subtlety

Example: M, channels A_1, A_2 (high input), X (high output), Y (low output).
Time 1: M inputs bits a_1 on A_1, a_2 on A_2, outputs random bit x on X.
Time 2: M outputs $y := a_1 \oplus a_2 \oplus x$ on Y ($\oplus$: exclusive or).

In Gray's model, M secure since $a_1 \oplus a_2$ independent from x, so y is 0 or 1 each with probability 1/2 independent of H.
But feedback of X into A_2 not secure: takes a value a_1 on A_1 at time 1 and outputs a_1 at time 2.

Our model allows environment's output to depend on input at same time (rushing adversary, B. Pfitzmann).

Thus M is correctly insecure.

Compositionality Theorem

Theorem: If M and N satisfy PNI, so does $M \otimes N$.

Proof uses rely-guarantee principle (inspired by Abadi, Lamport's which does not apply here (McLean 94)).

Inductive Compositionality: Setting

$\mathcal{S}$ set of "systems", $\mathcal{E}$ of "environments"; $\mathcal{S} \subseteq \mathcal{E}$.

$\otimes$ binary composition on $\mathcal{E}$ restricting to $\mathcal{S}$.

For each $t \in \mathbb{N}_{\geq 0}$ have properties $\phi_t \subseteq \mathcal{E}$ and $\sigma_t \subseteq \mathcal{S} \times \mathcal{E}$ with $\phi_0 = \mathcal{E}$, $\sigma_0 = \mathcal{S} \times \mathcal{E}$.

If $(M, E) \in \sigma_t$ say M guarantees σ_t in E.

If M guarantees σ_t in any E satisfying ϕ_s say M guarantees σ_t assuming ϕ_s.

Write ϕ for $\bigwedge_t \phi_t$ and σ for $\bigwedge_t \sigma_t$.

Suppose if M guarantees σ_{t+1} assuming ϕ_{t+1}, then M guarantees σ_t assuming ϕ_t (each t, M).

Also M guarantees σ assuming ϕ iff for all t, M guarantees σ_t assuming ϕ_t.

Inductive Compositionality: Result

Suppose that for each t:

a) For any E, if E satisfies ϕ_{t+1} and M guarantees σ_t assuming ϕ_t and "guarantee σ_t assuming ϕ_t" is compositional, then $E \otimes M$ satisfies ϕ_{t+1}.

b) For all E, M_1, M_2: $M_1 \otimes M_2$ guarantees σ_t in E if

- M_1 guarantees σ_t in $E \otimes M_2$ and
- M_2 guarantees σ_t in $E \otimes M_1$.

If M_1 and M_2 guarantee σ assuming ϕ then $M_1 \otimes M_2$ guarantees σ assuming ϕ.

Nondeducibility-on-Strategies

Nonprobabilistic process $(I, O, \mathcal{H})$: $\mathcal{H}$ set of histories.

Strategy π for H assigns high input $a = \pi(w)$ to history $w \in \mathcal{E}_E$.

History $(x_1, y_1), (a_1, b_1,), \ldots, (a_t, b_t)$ compatible with strategy π if for each $s \leq t$, $\pi((x_1, y_1), (a_1, b_1,), \ldots, (x_s, y_s)) = a_s$.

Low history w_l compatible with π if exists history w with $w\lfloor_l = w_l$ such that w compatible with π.

w_l possible if exists strategy with which compatible.

Definition: M satisfies Nondeducibility-on-Strategies if for any π and any possible low history w_l there is a w compatible with π such that $w\lfloor_l = w_l$.

Probabilistic vs. Possibilistic: Embedding

For possibilistic M construct probabilistic $\widehat{M}$:
uniform distribution on possible outputs.

From probabilistic system M construct possibilistic system $|M|$:
history possible if has nonzero probability.

Theorem

a) Possibilistic M satisfies NOS iff $\widehat{M}$ satisfies PNI.

b) If probabilistic M satisfies PNI then $|M|$ satisfies NOS.

(Proof: uses Determinism Theorem.)

Related Work

Nonprobabilistic noninterference using process algebras:

CSP: translation of noninterference not suitable for FDR, also “refinement paradox”. Thus “noninterference through determinism” (Roscoe, Woodcock, Wulf 95).
But too restrictive (Lowe 99, Mislove 00).

CCS: reformulation of NOS called BNDC (Focardi, Gorrieri 94).
Under suitable conditions equivalent to “determinism” approach.

Bi-directional “handshake” communication subtle: low behaviour may interfere with high behaviour, but not other way (Roscoe, Goldsmith 99)

Conclusion

Towards practical verification of Probabilistic Noninterference:

- Determinism Theorem
- Compositionality (using Inductive Compositionality Principle)
- relation to Nondeducibility-on-Strategies.

Further Work

expressed PNI using discrete Markov chains (probabilistic modelchecking, Kwiatkowska) using coinductive definition.

wrapper (Sewell, Vitek), derive overall "leakage"

nondeterminism, refinement