A Logic for Reasoning About Networked Secure Systems

Deepak Garg, Jason Franklin,
Dilsun Kaynar, Anupam Datta

Carnegie Mellon University

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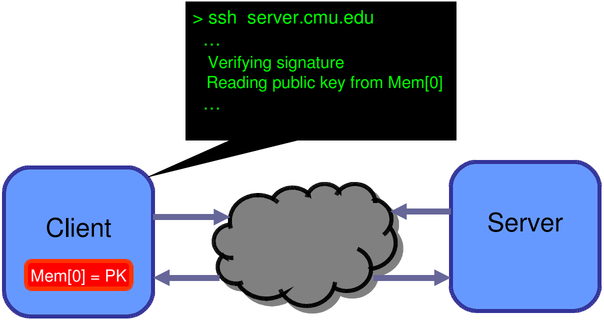
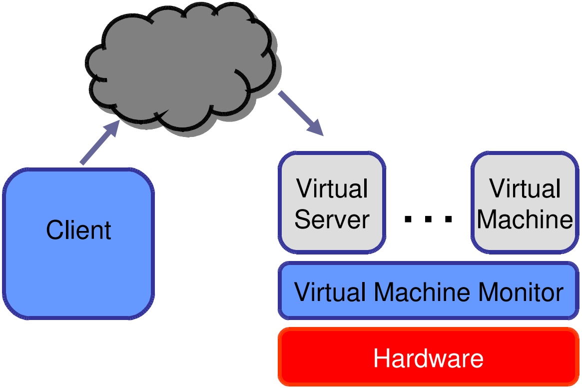
Example Secure Systems: OpenSSH



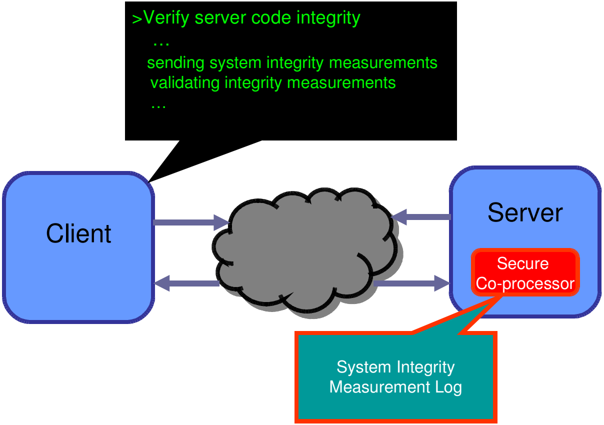
- Widely used remote secure shell [RFC 4253]
- Based on network and memory primitives

Example Secure Systems: Virtual Machine Monitors



- Widely deployed (e.g., VMware, Xen)
- Use memory protection and restricted APIs

Example Secure Systems: Trusted Computing



- Upcoming technology (Intel TXT, AMD SVM, Microsoft Bitlocker)
- Uses special registers, restricted APIs

Motivation and Project Goals

- Model secure systems and adversaries
- Specify security properties
- Prove that systems satisfy properties

- Composition of systems and proofs (e.g., SSH over VMM)
- Insights into implementation (e.g., trusted Grub bootloader)
- Comparison of alternative system designs (e.g., remote attestation vs late launch)

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Technical Contributions

- Framework: Logic of Secure Systems (LS^2)
  - Based on Protocol Composition Logic (PCL)
- Programming language to specify systems and adversaries
  - Operational semantics defines reduction traces
- Logic to specify security properties
  - Predicates interpreted over traces
- Proof system to establish security properties
  - Soundness theorem ensures provable properties hold over all traces

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Outline

1. Design choices
2. Programming language and logic
3. Semantics and soundness
4. Conclusion

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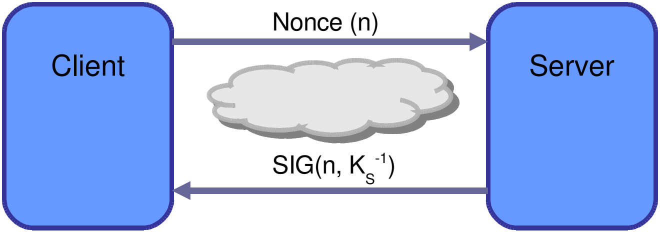
Secure System Primitives and Adversaries



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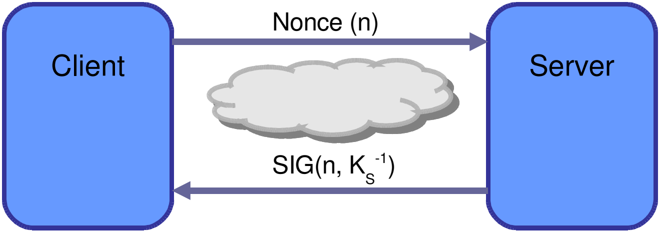

	Primitives	
Network (Standard)	- Send, receive - Crypto (sign, encrypt)	

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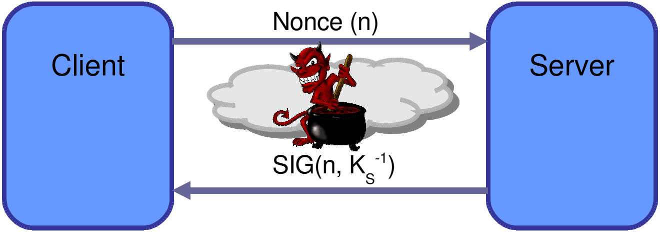

	Primitives	Adversary
Network (Standard)	- Send, receive - Crypto (sign, encrypt)	- Symbolic(Dolev-Yao)

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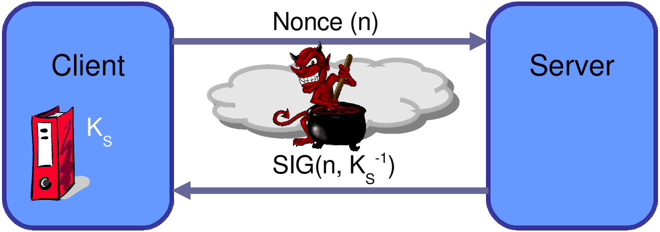

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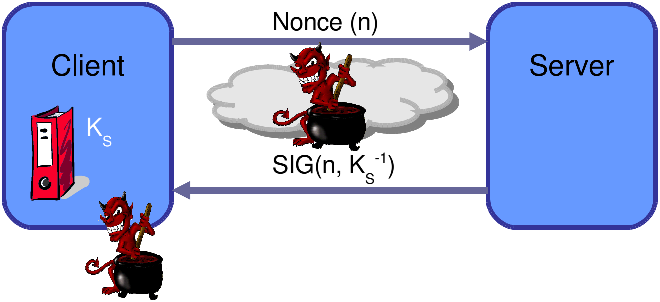

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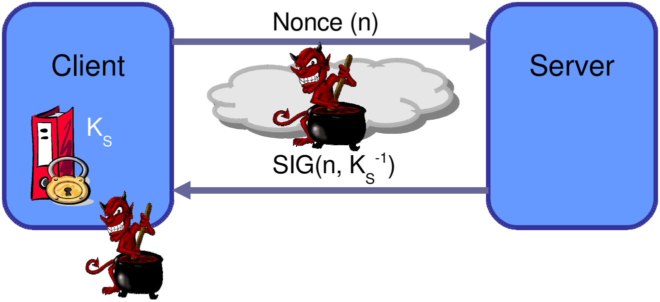

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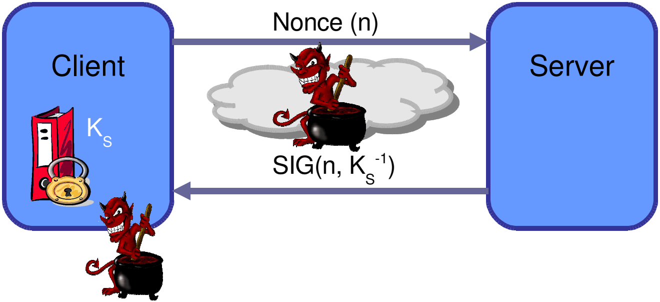

	Primitives	Adversary
Network (Standard)	- Send, receive - Crypto (sign, encrypt)	- Symbolic(Dolev-Yao)

- Identify secure system primitives
- Model adversary capabilities, as opposed to enumerating attacks

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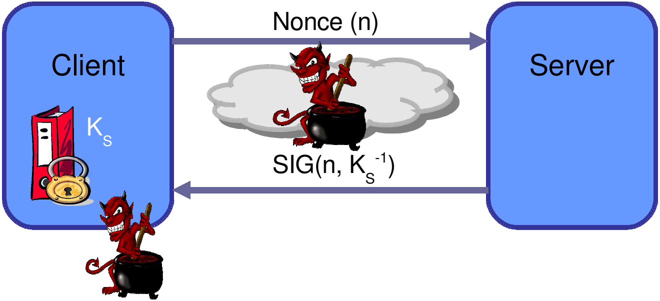

	Primitives	Adversary
Network (Standard)	- Send, receive - Crypto (sign, encrypt)	- Symbolic(Dolev-Yao)
Local (New)	- Shared RAM and files - Protection (access control)	- Steal, corrupt data - Corrupt code

New Primitives and Adversary Capabilities in LS^2

- Secure system primitives
  - Read, write locations of memory (RAM and persistent storage)
  - Exclusive-write locks for integrity
  - (Extension with exclusive-read locks for secrecy)

- Adversary capabilities
  - Read memory
  - Write to unlocked memory
  - Lock unlocked memory

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Programming Language

- Thread-oriented (process-calculus + explicit state)
  - Secure systems and adversaries modeled as threads

$$
\begin{array}{llcl}
\text{Action} & a & ::= & \texttt{send}\, e \\
& & \mid & \texttt{receive} \\
& & \mid & \texttt{sign}\, e, K^{-1} \\
& & \mid & \texttt{verify}\, e, K \\
& & \mid & \texttt{read}\, l \\
& & \mid & \texttt{write}\, l, e \\
& & \mid & \texttt{lock}\, l \\
& & \mid & \texttt{unlock}\, l \\
& & \mid & \texttt{proj}_1\, e \\
& & \mid & \texttt{proj}_2\, e \\
& & \mid & \texttt{match}\, e, e' \\
& & \mid & \texttt{new} \\
\text{Program} & P, Q & ::= & x_1 := a_1; \ldots; x_n := a_n
\end{array}
$$

- See paper for details and operational semantics

Specifying Security Properties

- Properties specified in a logic
- Logic models explicit time (real numbers)
  - Action happened at a specific time
  - A program executed in a specified interval of time
- Time needed to model some systems of interest
  - E.g., Pioneer, Genuinity, TESLA
- In reasoning,
  - Time used to order events
  - Time used to state invariants

Logic: Syntax

Predicates	R	$::=$	$\text{Send}(U, e) \mid \text{Receive}(U, e)$
		$\mid$	$\text{Sign}(U, e, K) \mid \text{Verify}(U, e, K)$
		$\mid$	$\text{Read}(U, l, e) \mid \text{Write}(U, l, e)$
		$\mid$	$\text{Lock}(U, l) \mid \text{Unlock}(U, l)$
		$\mid$	$\text{Match}(U, e, e') \mid \text{New}(U, n)$
	M	$::=$	$\text{Mem}(l, e)$
		$\mid$	$\text{IsLocked}(l, U)$
		$\mid$	$\text{Contains}(e, e')$
		$\mid$	$e = e' \mid t \geq t'$
		$\mid$	$\text{Honest}(\hat{X})$
		$\mid$	$\text{Honest}(\hat{X}, \vec{P})$
Formulas	A, B	$::=$	$R \mid M \mid \top \mid \bot \mid A \wedge B \mid A \vee B \mid$
			$A \supset B \mid \neg A \mid \forall x.A \mid \exists x.A \mid A \ @\ t$
Defined Formula	A on i	$=$	$\forall t.\ ((t \in i) \supset (A \ @\ t))$
Modal Formulas	J	$::=$	$[P]_U^{t_b, t_e}\ A \quad \mid \quad [a]_{U,x}^{t_b, t_e}\ A$

Proof System of the Logic

- Some axioms
  - Memory persists:

    $$\vdash (\mathrm{IsLocked}(l, U) \text{ on } [t_b, t_e) \wedge (\mathrm{Mem}(l, e) \ @\ t_b) \wedge (\forall e'. \neg \mathrm{Write}(U, l, e') \text{ on } [t_b, t_e))) \supset (\mathrm{Mem}(l, e) \text{ on } [t_b, t_e))$$

  - Locks persist:

    $$\vdash ((\mathrm{IsLocked}(l, U) \ @\ t) \wedge (\neg \mathrm{Unlock}(U, l) \text{ on } [t, t'))) \supset (\mathrm{IsLocked}(l, U) \text{ on } [t, t'])$$

- Local reasoning: Proofs analyze only system components, not adversaries (*cf.* Hoare Logic and PCL)
  - Non-trivial with shared memory (what if another thread changes memory?)
  - Feasible because of appropriate memory protections

- In ongoing work we are using the proof system to analyze trusted computing protocols

Correctness Theorem for Example

$$\boxed{\Gamma \vdash J \text{ in } LS^2\text{'s proof system}}$$

$$\Gamma \;=\; \text{Honest}(\hat{K}_s, \mathit{Server}(K_S^{-1})),\;\; \hat{U} \neq \hat{K}$$

$$J \;=\; [\mathit{Client}(m, K_S)]_U^{t_b, t_e} \quad \exists n.\exists t_g.\exists t_s.\exists U'.\ ((t_b < t_g < t_s < t_e) \wedge (\text{New}(U, n) \;@\; t_g) \wedge (\hat{U}' = \hat{K}_S) \wedge (\text{Sign}(U', n, K_S^{-1}) \;@\; t_s))$$

- Proof reasons about memory and network primitives
- Protocol secure in presence of local and network adversary
- See full paper for details

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Semantics and Soundness

- Semantics of logic defined w.r.t. traces of programs ($\mathcal{T}$)
  - A trace is a sequence of reductions of a set of threads
  - We associate monotonically increasing time points with reductions
- Semantic relations:
  - $\mathcal{T} \models^{t} A$
  - $\mathcal{T} \models [P]_{U}^{t_b,t_e} A$
- Example:
  - $\mathcal{T} \models [P]_{U}^{t_b,t_e} A$ if whenever the reductions of thread U in the interval $[t_b, t_e)$ on trace $\mathcal{T}$ match P, it is the case that A holds.
- Soundness Theorem:

  If $\Gamma \vdash \varphi$ then $\Gamma \models \varphi$

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Ongoing Work

- Application to trusted computing
  - E.g., remote attestation protocol
  - E.g., sealed storage protocol
- More primitives and stronger adversary
  - Special hardware: PCRs, secure coprocessor
  - Adversaries that can reset machines
  - Adversaries that can modify code
- Unchanged memory model
- Composition of systems and proofs
  - E.g., sealed storage after remote attestation

Conclusion

- Advanced secure systems, formal techniques lacking
- Identifying relevant primitives, and modeling them
  - E.g., shared memory, memory protection, . . .
- Specifying adversary capabilities instead of enumerating attacks
  - E.g., steal and corrupt data, corrupt code, reset machines
- Reasoning about security properties in presence of such adversaries
  - LS^2 supports local reasoning
- Technical contribution:
  - Programming language, logic, proof system, semantics
  - Soundness theorem

Thank You

Questions?

Extra Slides

Dense Time

- We assume a dense model of time
- Density does not appear in proof system
- Density needed to prove soundness

$$\frac{\vdash [a]_{I,x}^{t_b,t_m}\ A_1 \qquad \vdash [P]_{I}^{t_m,t_e}\ A_2 \qquad (t_m \text{ fresh})}{\vdash [x := a; P]_{I}^{t_b,t_e}\ \exists t_m.\exists x.\ ((t_b < t_m < t_e) \wedge A_1 \wedge A_2)}\text{Seq}$$