Formal verification of side-channel attacks

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Motivation

- Cryptographic algorithms are provably secure
- But many cryptographic libraries are broken
  - implementation bugs
  - bad randomness
  - side-channels
  - ...

Formal verification of side-channels

- Writing secure implementations is notoriously hard
- Empirical evaluations are useful but insufficient
- Difficult to interpret theoretical approaches

Objective:

(automated) formal guarantees for real implementations

Case studies:

- Cache-based timing attacks
- Differential power analysis

Commonalities:

- modelling approach
- (relational) program verification
- non-trivial interactions with provable security

Modelling

- Precise modelling of CPU is not desirable
- We need good trade-offs between accuracy and tractability

$$\text{model is too simple} \implies \text{missed attacks}$$
$$\text{model is too complex} \implies \text{verification unfeasible}$$

Standard warnings:

$$\text{models are constructed} \implies \text{attacks outside the model}$$
$$\text{proof fails} \not\implies \text{practical attack}$$

Formal models should match practitioners's view:

- Likely to yield tractable models
- Do not roll your own models

Ideally, formal models can be validated

Constant-time cryptography

- Control flow does not depend on secrets

  $$\text{if } H \text{ then } s_1 \text{ else } s_2$$

- Memory accesses do not depend on secrets

  $$a[H]$$

  (array is public)

Why care?

- Best practice against cache attacks
- Non-constant-time implementations are often easily broken
- No panacea: execution time of instruction may depend on operands, does not account for micro-architectural attacks

Sanity check: language-level vs system-level

Language-level security

Constant-time is a (non-standard) information flow policy:
leakage does not depend on secrets

System-level security

Constant-time program is protected against adversary

- executing on same virtualized platform
- controlling the cache
- controlling the scheduler
- under all realistic replacement policies

(Mechanized) proof based on idealized model of virtualization:
no branch prediction, no interrupt

Formalizing constant-time security

Observational non-interference

- Define leakage model
- Show that leakage is independent of secret
  Executions (with different secrets) have equal leakage

Variant with public outputs

Verifying constant-time security

- Build product program

$$\text{if } e \text{ then } s \text{ else } s' \rightsquigarrow \text{assert } e_1 = e_2; \text{if } e_1 \text{ then } p \text{ else } p'$$

- Check

$$m_1 =_L m_2 \Longrightarrow p, m_1 \uplus m_2 \not\Downarrow \bot$$

- Flexible, compatible with off-the-shelf verifiers
- Sound and relatively complete
- Extensively evaluated

Enforcing constant-time security

- Start from information flow secure program
  - no high loop
  - no secret dependent memory access
- Eliminate high conditionals, early termination, etc.
- Flexible, allows programmers to write readable code
- Seriously evaluated

Constant-time security: challenges

- Post-quantum cryptography
- Secure compilation
- Constant-time security under speculative execution

Constant-time and post-quantum cryptography

$b \leftarrow \mathbf{tt};$
while b do $r \xleftarrow{\$} \mu; y \leftarrow f(x, r); b \leftarrow P(y)$
return y

- Challenges: control-flow, non-uniform distributions
- One approach (for control-flow): leak guards
- But: security proof must be strengthened
- Another approach: use an alternative algorithm (GALACTICS)

Preservation of software-based countermeasures

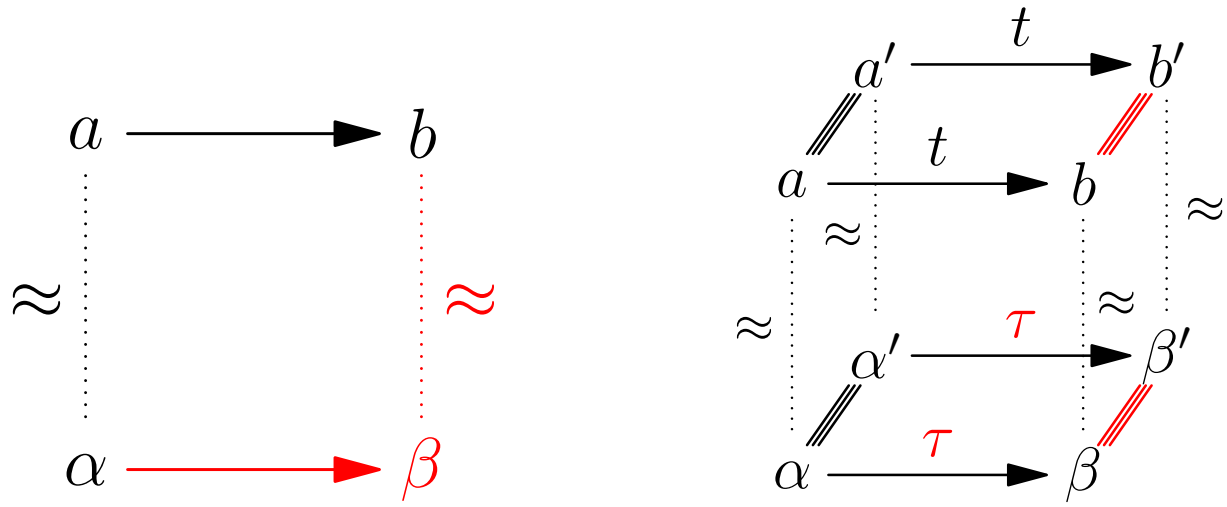
Does my optimization preserve constant-time?

- Some optimizations break constant-time
- However many optimizations don't

Techniques and case studies:

- CT-simulations (and simplifications)
- Jasmin (on paper) and CompCert (in Coq)

CT simulations



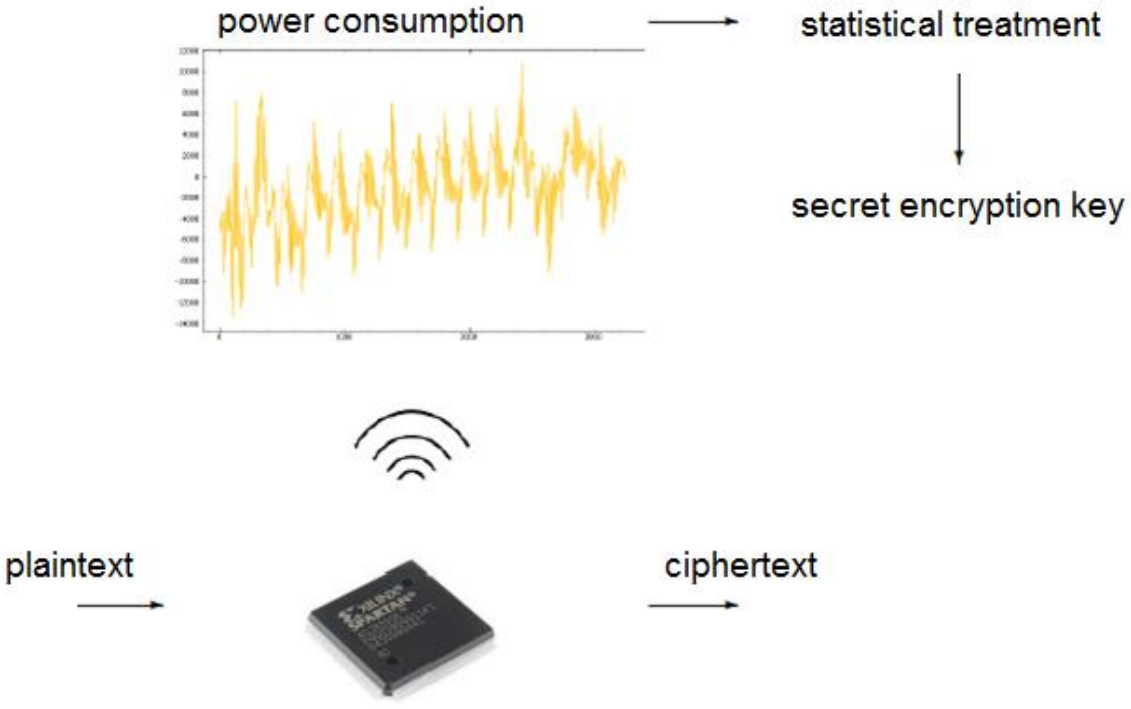
- Each target step is related to a source step (simulation proof)
- Prove that target leakages are equal for every two instances of the simulation diagram with equal source leakage
- Therefore source-level CT implies target-level CT
- Three variants: lockstep, one to several, one to any (number of steps must be explicit and uniform)

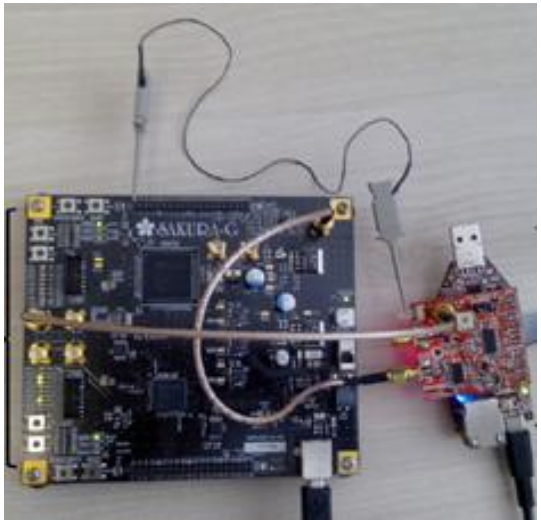
Simpler approaches

- Preserving, erasing or renaming leakage
- Case study: CompCert

Compiler pass	Uses	
Cshmgen	Leakage pres.	Type elaboration, simpl. of control
Cminorgen	Memory inj.	Stack allocation
Selection	Leakage erasing	Sel. of operators and addr. modes
RTLgen	Leakage pres.	Generation of CFG and 3-address code
Inlining	Leakage transf.	Function inlining
ConstProp	Leakage transf.	Constant propagation
CSE	Leakage erasing	Common subexpression elimination
Deadcode	Leakage erasing	Redundancy elimination
Allocation	Leakage erasing	Register allocation
Tunneling	Leakage erasing	Branch tunneling
Linearize	CT-simulation	Linearization of CFG
Stacking	Memory inj.	Laying out stack frames
Asmgen	Leakage transf.	Emission of assembly code

Power analysis





Recover secrets from measuring power consumption

- SPA: single trace
- DPA: multiple traces

Serious threat for embedded systems

Masked implementations

- Values x encoded as probabilistic $t+1$-tuples $(x_0 \dots x_t)$ s.t.
  - $x_0, \dots, x_t$ are i.i.d. w.r.t. to uniform distribution
  - $x = x_0 + \dots + x_t$
- Operations operate on probabilistic values:
  - linear operations: apply the function to each share
  - non-linear operations: harder

Function SecMult(a,b)
$ab_{0,0} \leftarrow a_0 \cdot b_0; ab_{0,1} \leftarrow a_0 \cdot b_1; ab_{0,2} \leftarrow a_0 \cdot b_2;$
$ab_{1,0} \leftarrow a_1 \cdot b_0; ab_{1,1} \leftarrow a_1 \cdot b_1; ab_{1,2} \leftarrow a_1 \cdot b_2;$
$ab_{2,0} \leftarrow a_2 \cdot b_0; ab_{2,1} \leftarrow a_2 \cdot b_1; ab_{2,2} \leftarrow a_2 \cdot b_2;$
$r_{0,1} \xleftarrow{\$} \mathbb{F}_{256}; r_{0,2} \xleftarrow{\$} \mathbb{F}_{256}; r_{1,2} \xleftarrow{\$} \mathbb{F}_{256}$
$r_{1,0} \leftarrow (r_{0,1} + ab_{0,1}) + ab_{1,0}$
$r_{2,0} \leftarrow (r_{0,2} + ab_{0,2}) + ab_{2,0}$
$r_{2,1} \leftarrow (r_{1,2} + ab_{1,2}) + ab_{2,1}$
$c_0 \leftarrow (ab_{0,0} + r_{0,1}) + r_{0,2}$
$c_1 \leftarrow (ab_{1,1} + r_{1,0}) + r_{1,2}$
$c_2 \leftarrow (ab_{2,2} + r_{2,0}) + r_{2,1}$
return (c_0, c_1, c_2)

Probing security, formally

Program c is secure at order t iff

- every set of observations of size $\leq t$ can be simulated with at most $\leq t$ shares from each input;
- the joint distribution for a set of observations of size $\leq t$ is independent from secrets

Relation to information flow

- Independence from secrets $\approx$ non-interference
- Opportunity to leverage programming language techniques

Validating the security model:

- equivalence with noisy leakage model
- experimentally

Challenges

Verification:

- Independence from secrets
- Combinatorial explosion
  - First-order masking:
    100 observation sets for a program of 100 lines
  - Second-order masking:
    4,950 observation sets for a program of 100 lines
  - Fourth-order masking:
    3,921,225 observation sets for a program of 100 lines

  Moreover, size of programs grows quadratically with order
- Composition

Optimization

- Randomness complexity
- Parallelization
- etc

Checking independence from a secret s

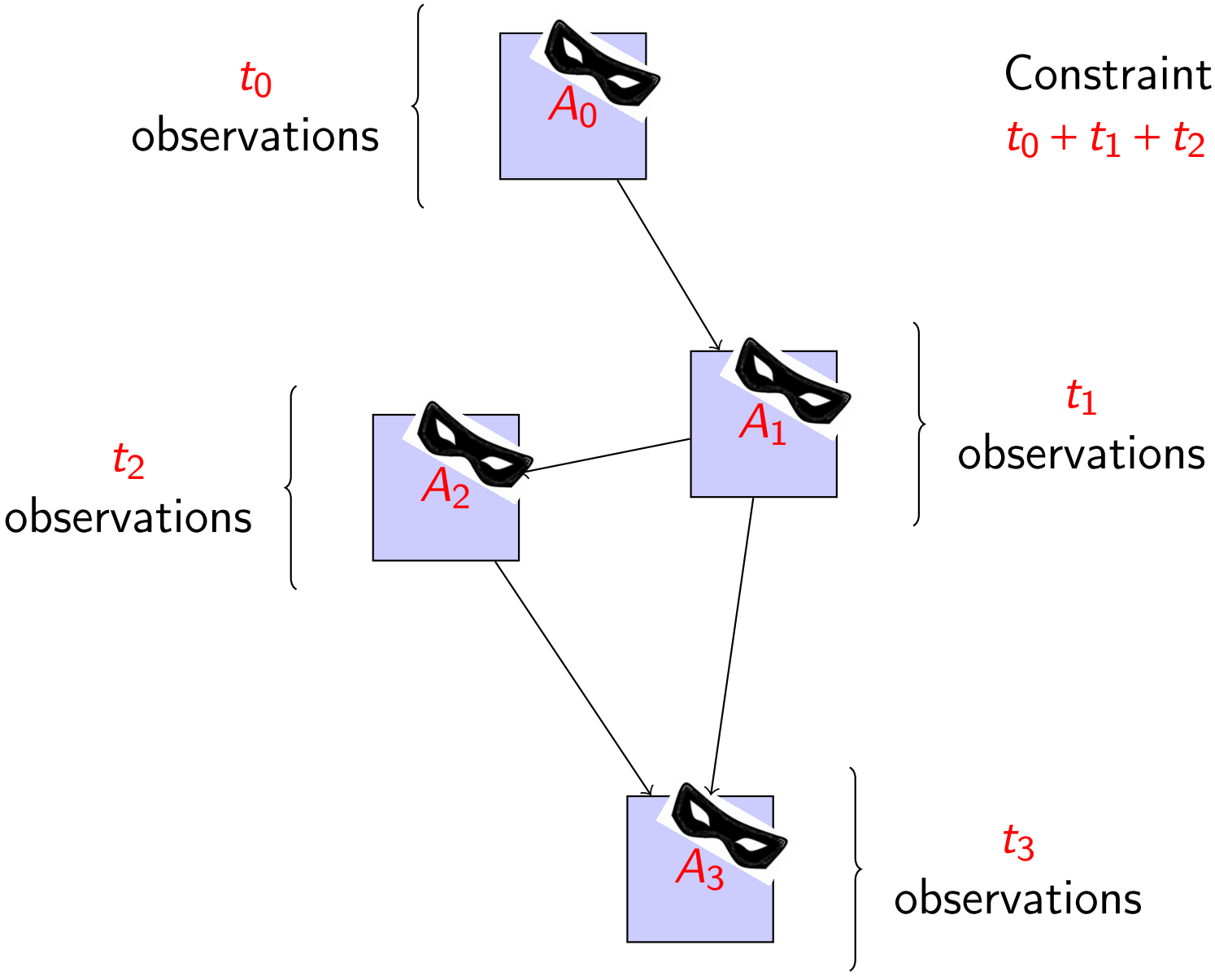
Sets of observations is modelled by tuple e of expressions

- Rule 1: If e does not use s then it is independent
- Rule 2: If e can be written as $C[f \oplus r]$ and r does not occur in C and f then it is sufficient to test the independence of $C[r]$
- Rule 3: Apply decision procedure, or compute distribution

Benefits

- easy to automate
- extends to large sets
- works on individual gadgets up to small orders

Composition

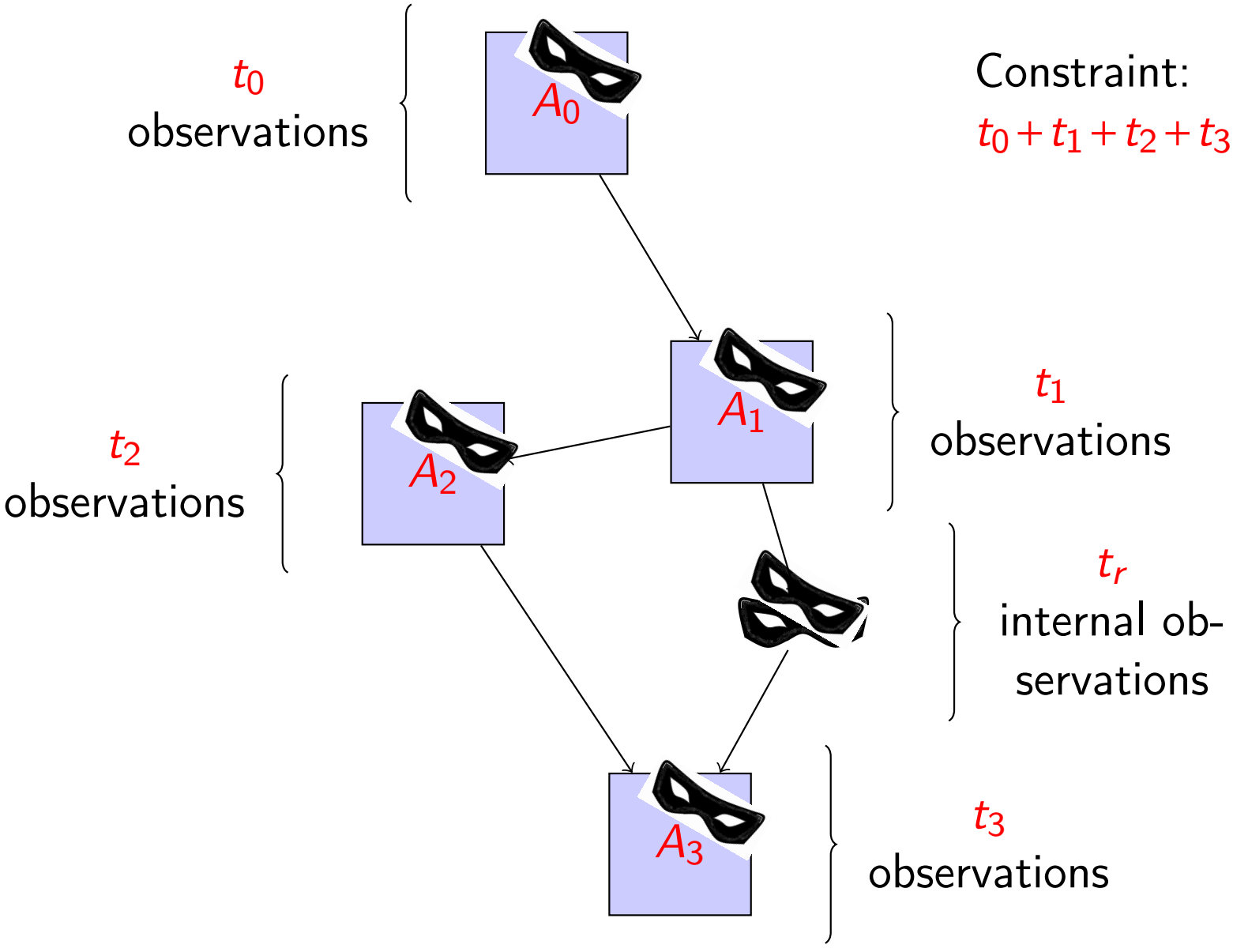


Strong non-interference

- distinguish between output and internal variables
- show that any set of t intermediate variables with
  - t_1 on internal variables
  - $t_2 = t - t_1$ on the outputs

  can be simulated with at most t_1 shares of each input

Secure Composition



Tools

MaskVerif

- Check probabilistic non-interference for large sets
- Probing security, NI, SNI, glitches
- Synthesis of refreshing gadgets

MaskComp

- Type-based information flow analysis
- Automated insertion of refresh gadgets
- Generate code at arbitrary orders
- Reasonably efficient at small orders

Execution times

Algorithm	unmasked	Order 1	Order 2	Order 3
AES	0.078s	2.697s	3.326s	4.516s
Keccak	0.238s	1.572s	3.057s	5.801s
Simon	0.053s	0.279s	0.526s	0.873s
Speck	0.022s	4.361s	10.281s	20.053s

Algorithm	Order 5	Order 10	Order 15	Order 20
AES	8.161s	21.318s	38.007s	59.567s
Keccak	13.505s	42.764s	92.476s	156.050s
Simon	1.782s	6.136s	11.551s	20.140s
Speck	47.389s	231.423s	357.153s	603.261s

Masking: challenges

- More security models
- More composition results
- Secure compilation
- Post-quantum cryptography

Beyond side-channel verification

- High-speed cryptography
  - low-level optimizations
  - partially written in assembly
  - no formal guarantees (mostly)
- High-assurance cryptography
  - functional verification (mainly)
  - side-channel (sometimes)
  - cryptographic strength (maybe)
  - written in C-like languages
    - compiler is in the TCB
    - reasonably efficient, but no match for high-speed crypto

Goal: high-assurance and high-speed cryptographic libraries

Fast and verified assembly implementations

A holistic approach

- Algorithm is provably secure
- Reference implementation is safe and functionally correct
- Optimized implementation is functionally equivalent to reference implementation and (co-)safe
- Optimized implementation is leakage-free

Optimized implementation is functionally correct and provable secure against implementation-level adversary

A recent case study: SHA3

- reference and vectorized assembly implementation of SHA3
- functionally equivalent and correct
- indifferentiable from RO

EasyCrypt

Domain-specific proof assistant for

- tailored to relational and game-hopping proofs
- control and automation from state-of-art verification
  - interactive proof engine and mathematical libraries (a la Coq/ssreflect)
  - back-end to SMT solvers

Many case studies:

- Encryption, signatures, key exchange, zero-knowledge, multi-party and verifiable computation, SHA3, voting, KMS
- Private Statistics, Smart Sum, Vertex Cover, Sparse Vector
- SGD, Glauber dynamics, population dynamics, card shufflings

Jasmin

- "Assembly in the head": mix of high-level constructs (variable names, global parameters, loops, functions) and low-level instructions and intrinsics
- Predictable and formally verified compiler
- Verification-friendly: safety, constant-time, functional correctness and equivalence checking (via EasyCrypt back-end)

Directions

- Support for other platforms
- Cautiously enrich language

Conclusions

- Practical tools for (specific) side-channels
- Interesting interactions with provable security
- “Practical” tools for correctness and provable security
- The future is fast and verified!