Proof-Carrying Data and Hearsay Arguments from Signature Cards

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Motivation

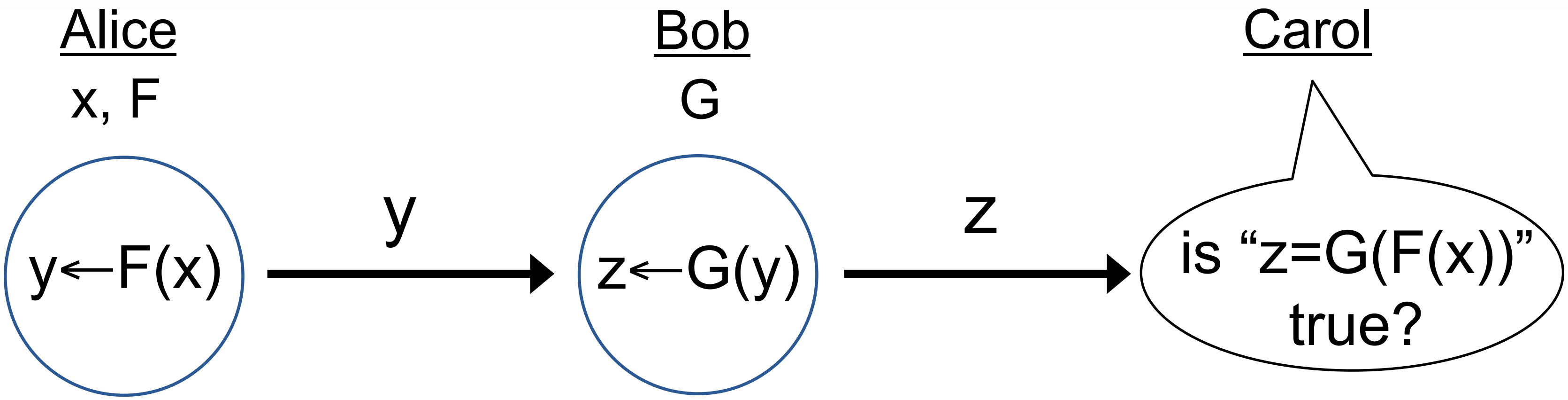
System and protocol security often fail when assumptions about software, platform, and environment are violated.

PLATFORM	SOFTWARE	ENVIRONMENT
bug attacks	bugs	physical side channels
architectural side channels	trojans	tampering
hardware trojans		

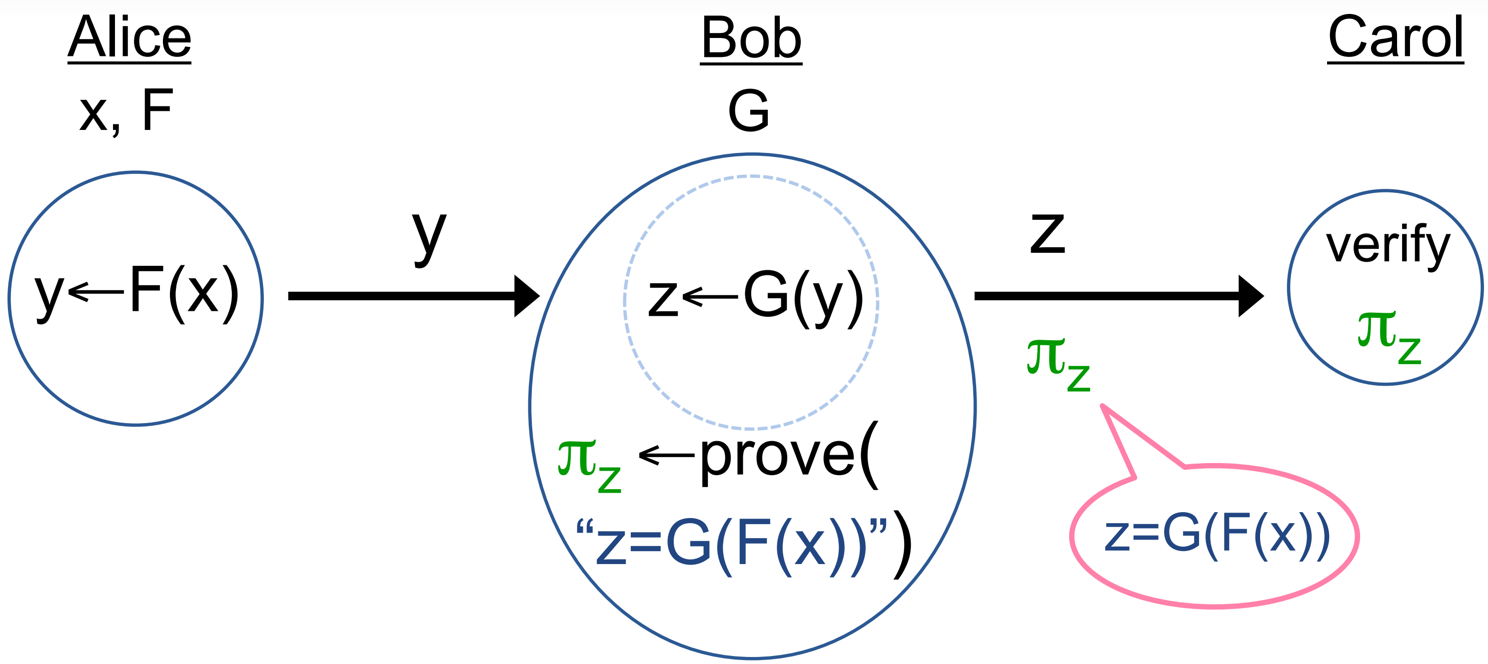
High-level goal

Ensure properties of a
distributed computation
when parties are
mutually untrusting,
faulty, leaky
&
malicious.

Example: 3-party correctness



Example: computationally-sound (CS) proofs [Micali 94]

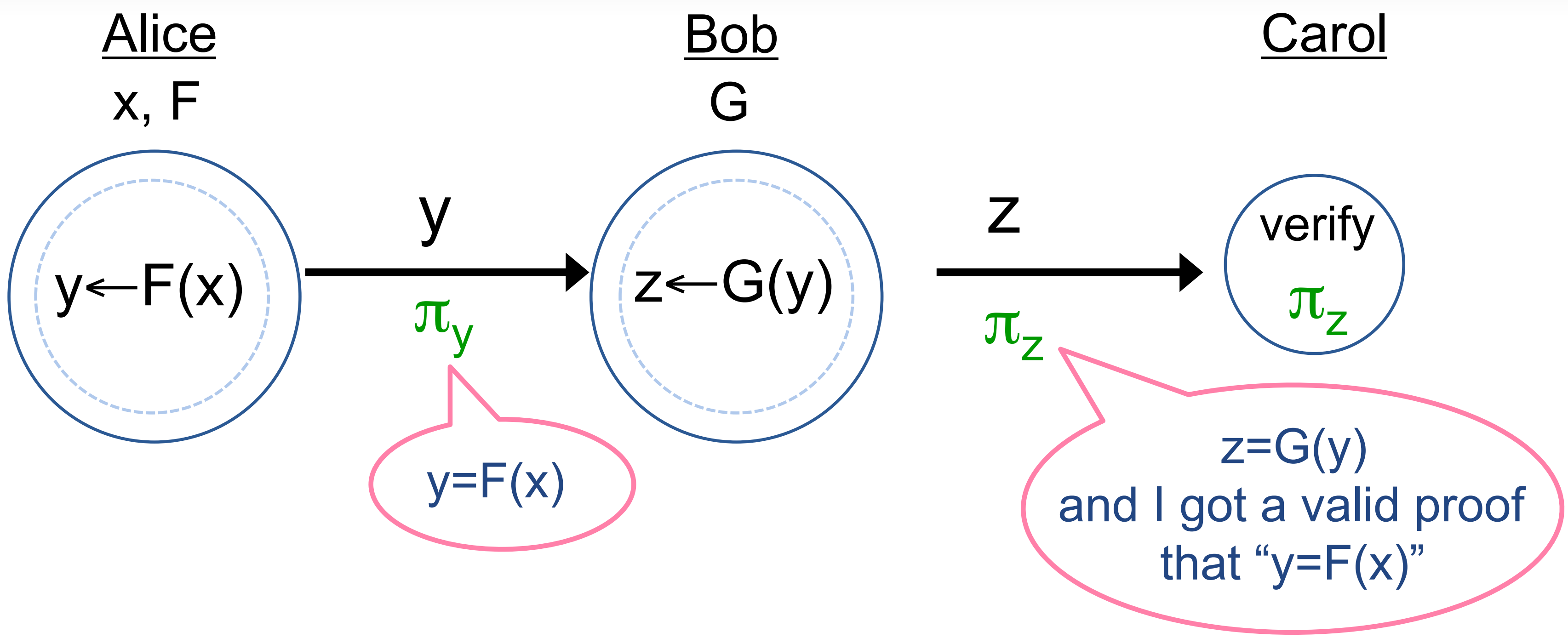


Bob can generate a proof string that is:

- Tiny (polylogarithmic in his own computation)
- Efficiently verifiable by Carol

However, now Bob recomputes everything...

Example: Proof-Carrying Data [Chiesa Tromer 09] following Incrementally-Verifiable Computation [Valiant 08]



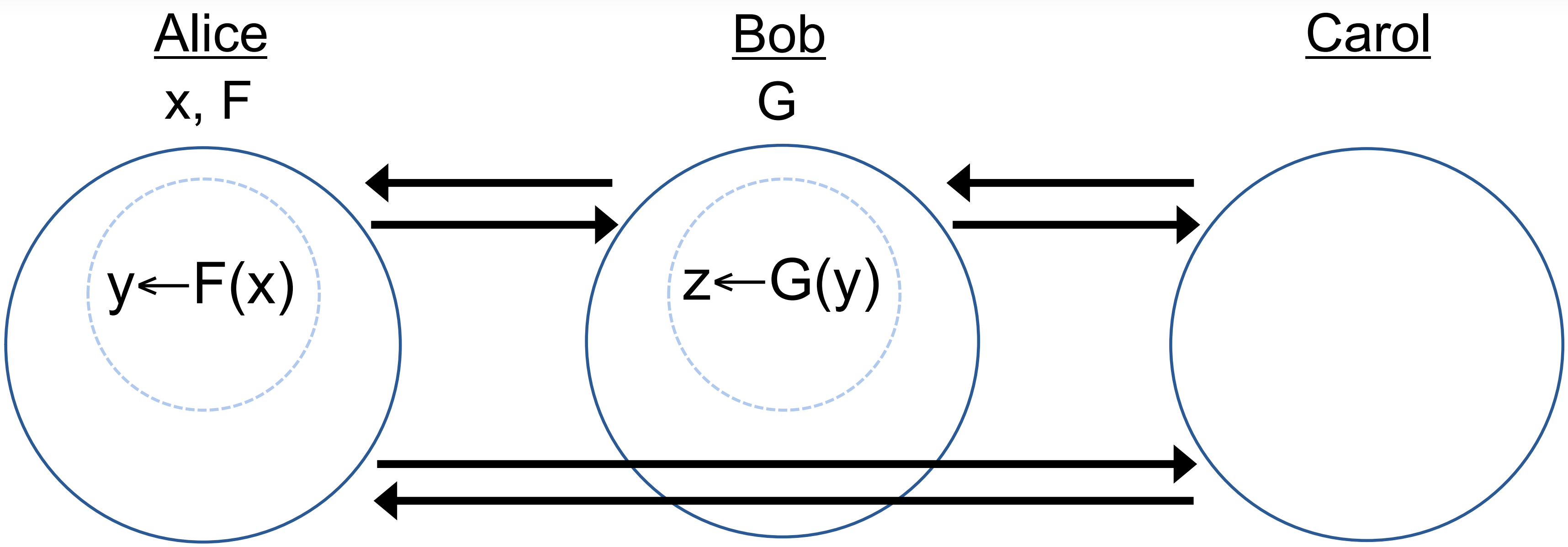
Each party prepares a proof string for the next one.

Each proof is:

- Tiny (polylogarithmic in party's own computation).
- Efficiently verifiable by the next party.

Related work:

Secure multiparty computation [GMW87][BGW88][CCD88]



But:

- computational blowup is polynomial in the whole computation, and not in the local computation
- does not preserve communication graph
- parties and computation must be fixed in advance

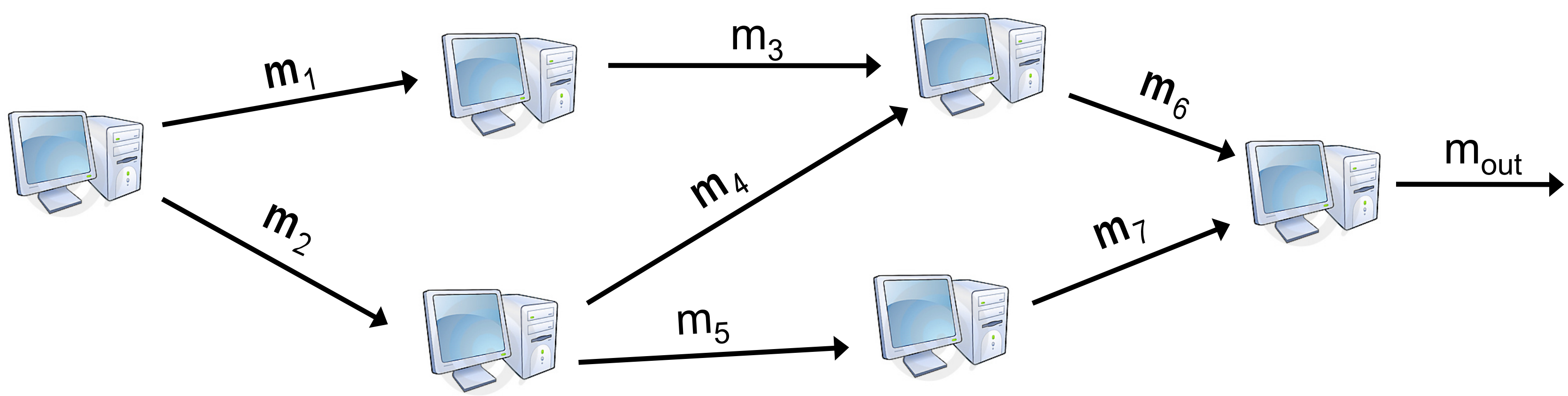
Generalizing:

The
Proof-Carrying Data
framework

Generalizing: distributed computations

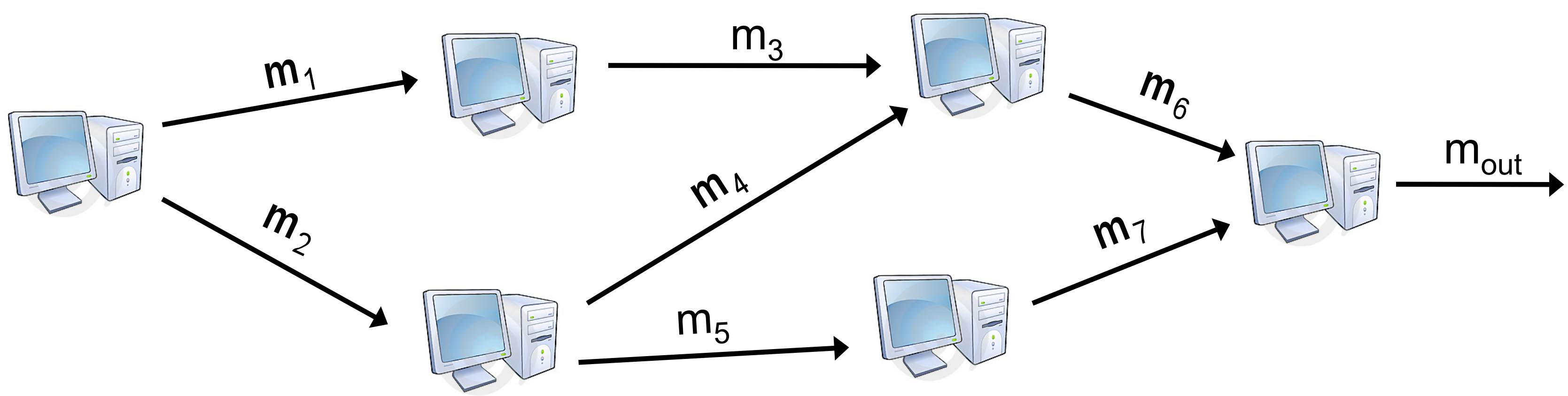
Distributed computation?

Parties exchange messages and perform computation.



Generalizing: arbitrary interactions

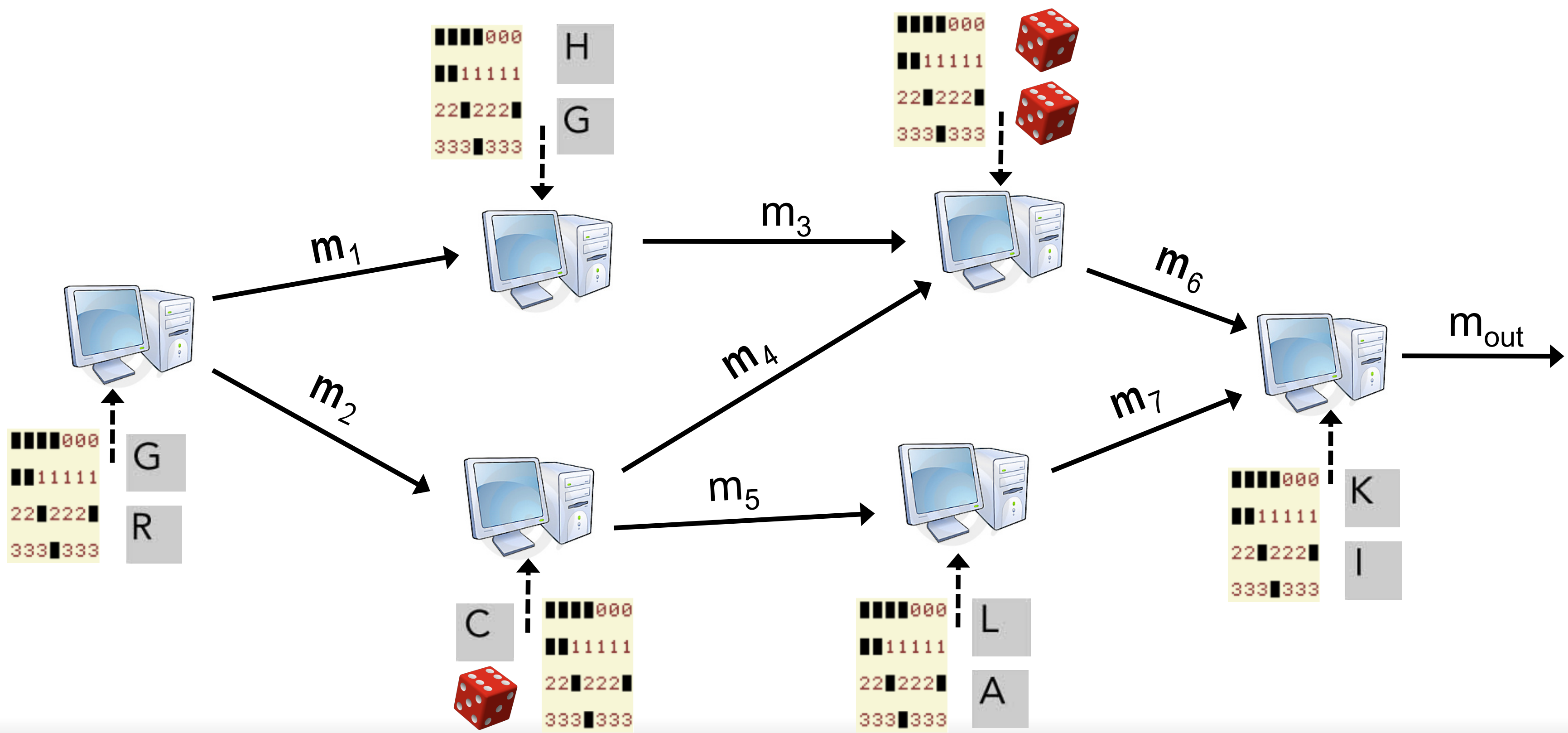
- Arbitrary interactions
  - communication graph over time is any DAG



Generalizing: arbitrary interactions

- Computation and graph are determined on the fly
  - by each party's local inputs:

human inputs randomness program



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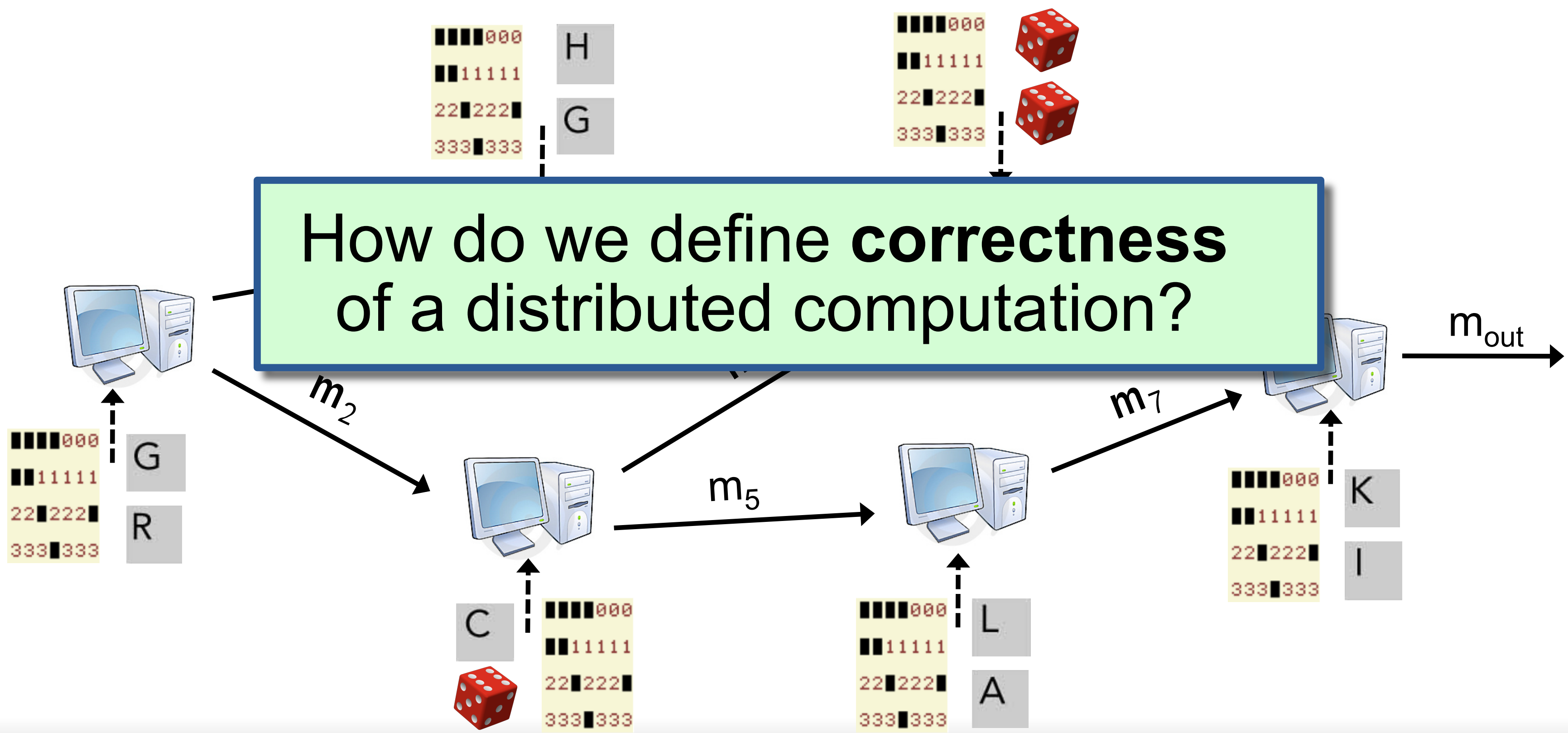

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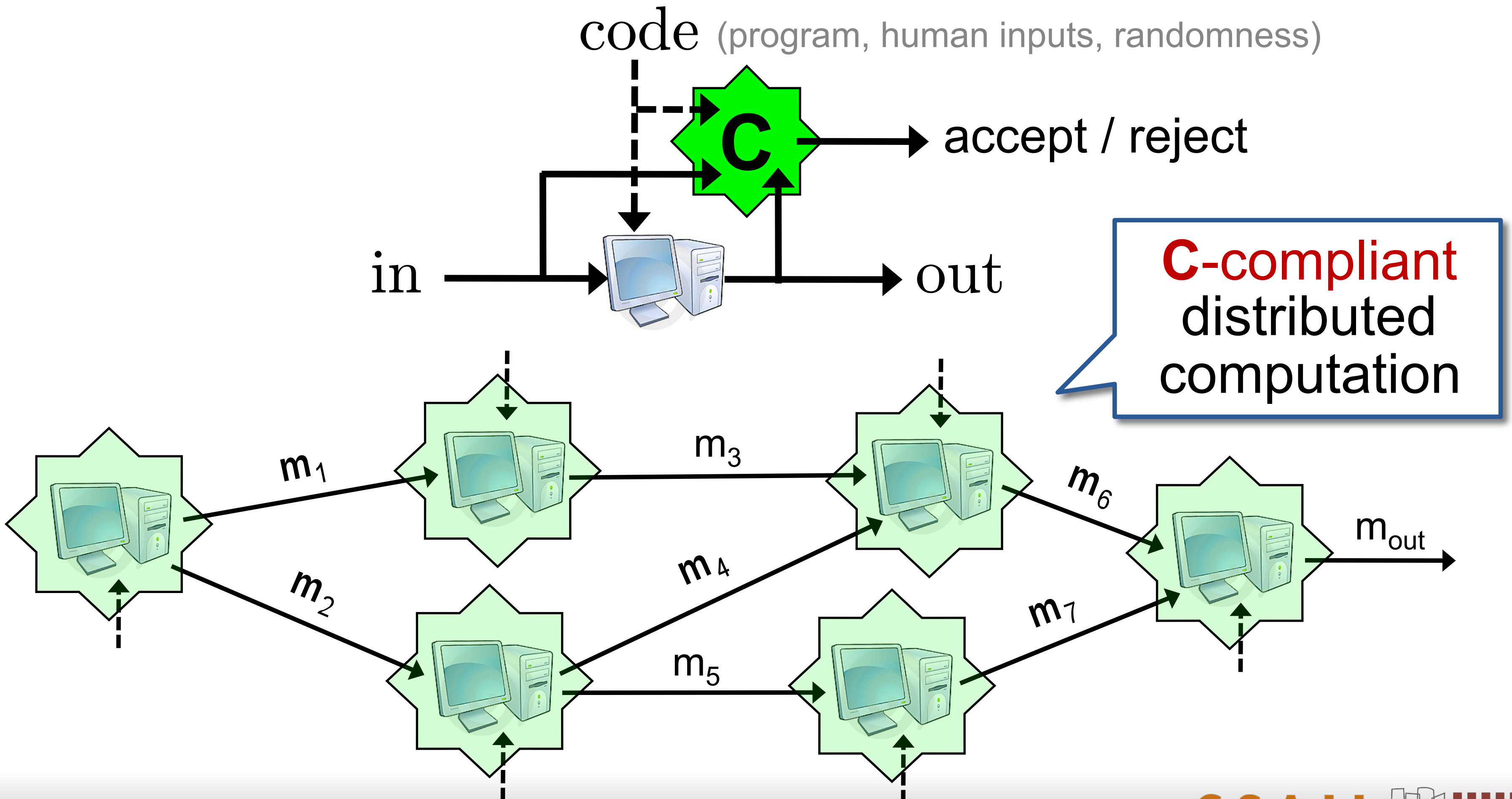
C-compliance

correctness is a **compliance predicate** **C**(in,code,out)
that must be locally fulfilled at every node



C-compliance

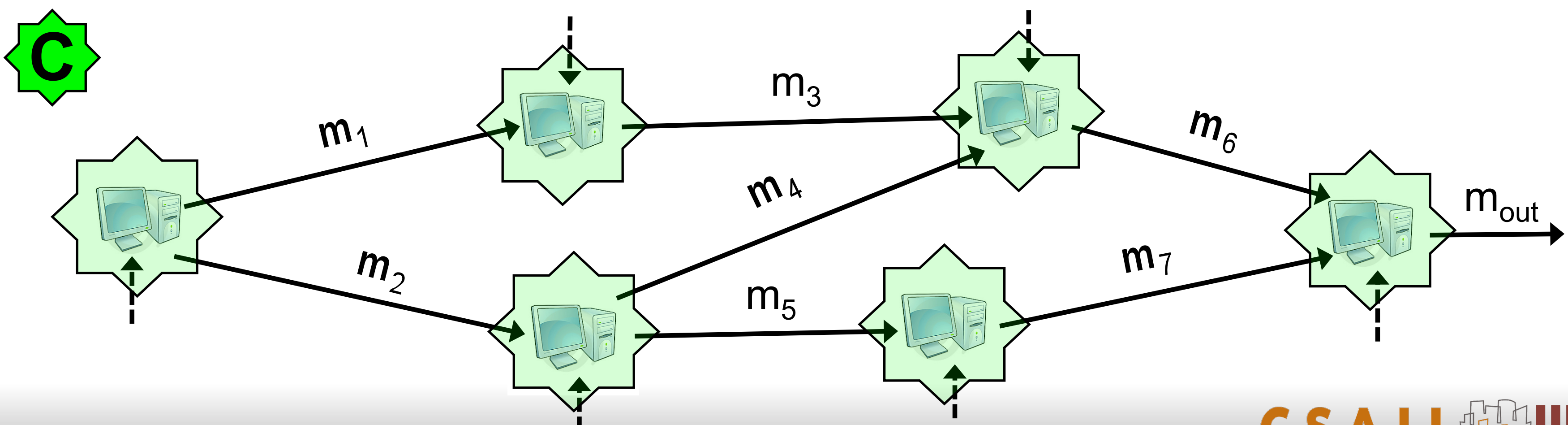
correctness is a **compliance predicate C**$(\mathrm{in},\mathrm{code},\mathrm{out})$
that must be locally fulfilled at every node

Some examples:

C = “none of the inputs are labeled `secret`”

C = “the code was digitally signed by the sysadmin, and executed correctly”

C = “the code is type-safe and the output is indeed the result of running the code”



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Goals

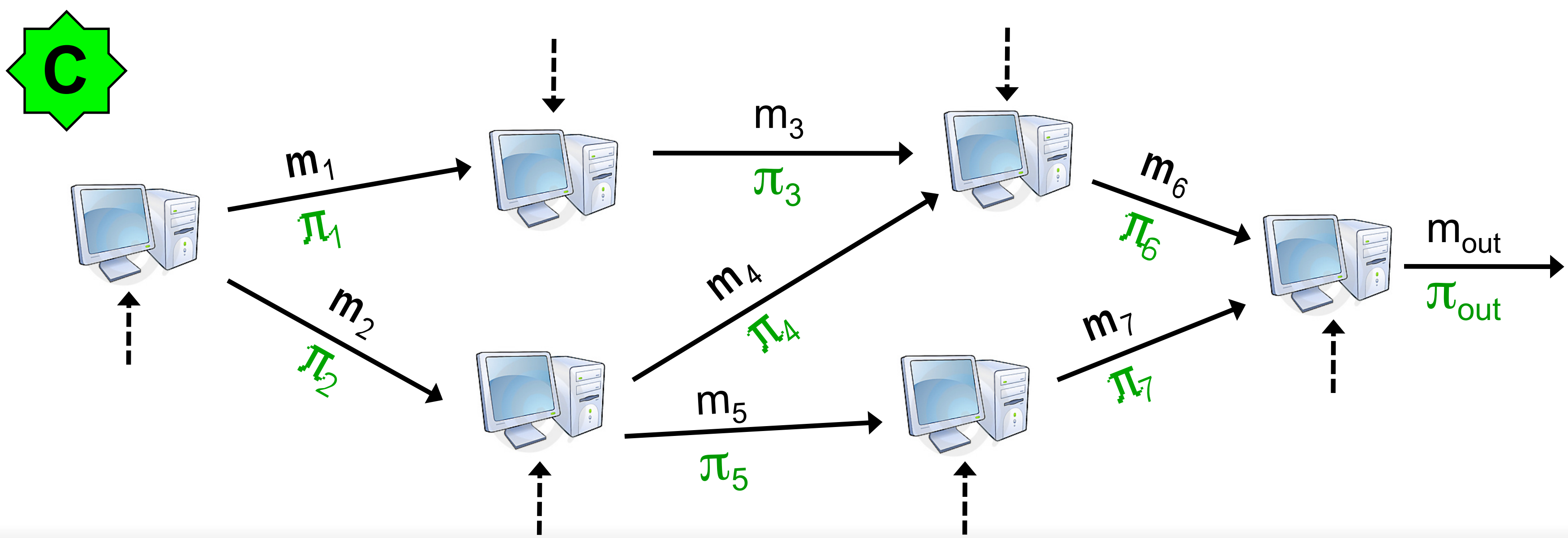
Ensure **C**-compliance while **respecting** the original distributed computation.

- Allow for any interaction between parties
- Preserve parties' communication graph
  - no new channels
- Allow for dynamic computations
  - human inputs, indeterminism, programs
- Blowup in computation and communication is local and polynomial

Dynamically augment computation with proofs strings

In PCD, messages sent between parties are augmented with concise proof strings attesting to their “compliance”.

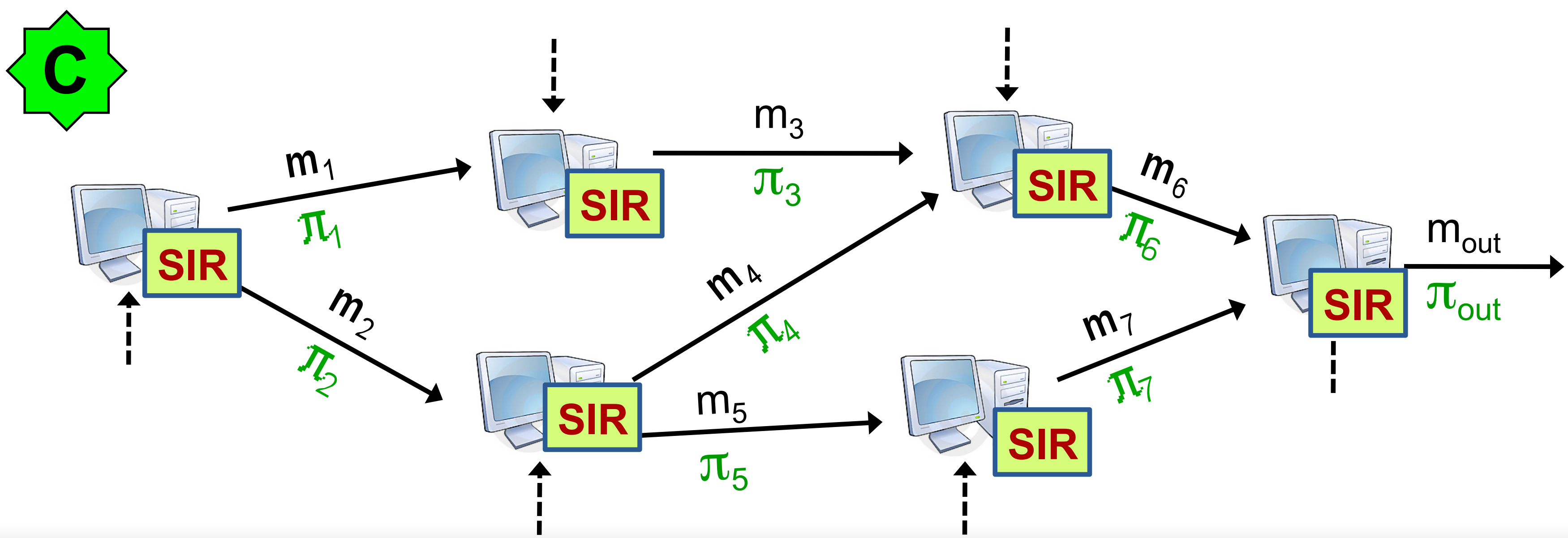
Distributed computation evolves like before, except that each party also generates on the fly a proof string to attach to each output message.



Model

Every node has access to a simple, fixed, stateless trusted functionality -- essentially, a signature card.

- Signed-Input-and-Randomness (SIR) oracle



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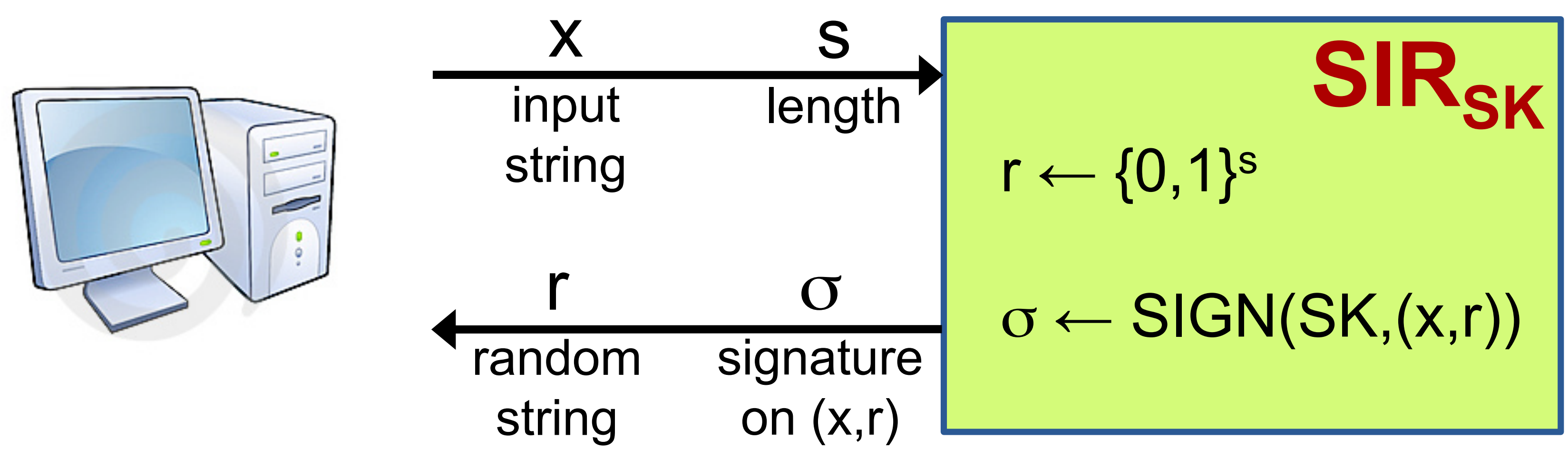


Similar assumptions:
[Hofheinz Müller-Quade Unruh 05]

VK

Sample application: type safety

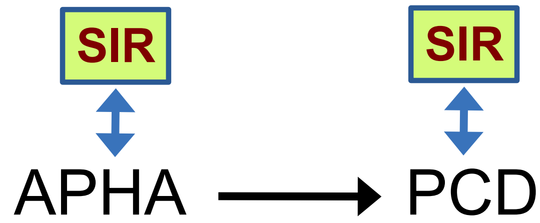
C(in,code,out) verifies that
code is type-safe & $\text{out}=\text{code}(\text{in})$

- Using PCD, type safety can be maintained
  - even if underlying execution platform is untrusted
  - even across mutually untrusting platforms

- Type safety is very expressive
  - Can express any computable property
  - Extensive literature on types that can be verified efficiently (at least with heuristic completeness, which is good enough)
  - E.g., can do certain forms of confidentiality via IFC

Our results

Overview of Results



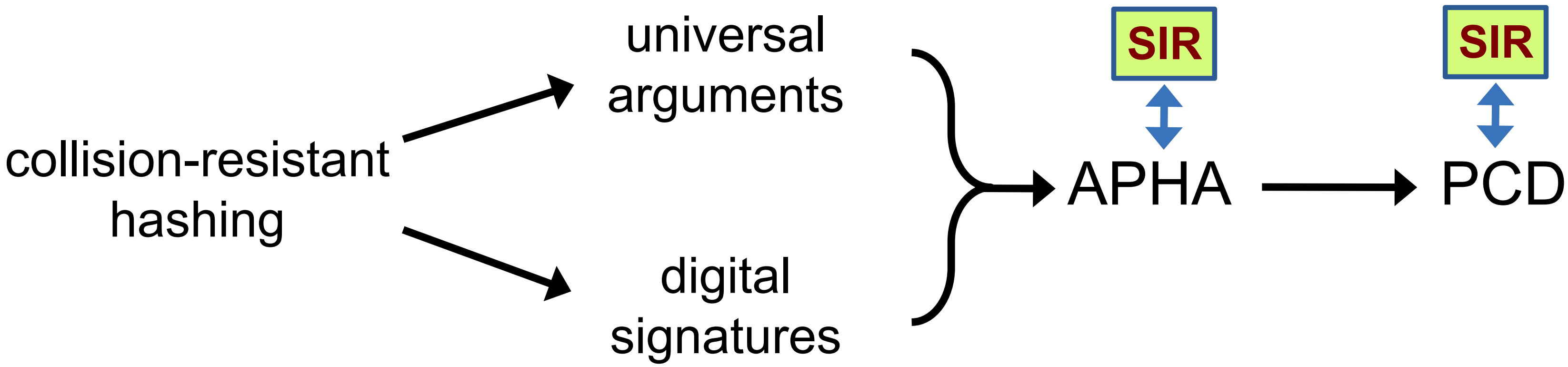
Proof-Carrying Data (PCD):

- **C**-compliance
- Aggregate proof strings to generate new ones
- Simpler interface hides implementation details

Assisted-Prover Hearsay-Arguments (APHA):

- Very strong variant of non-interactive CS proofs / arguments of knowledge (for NP)
- Proof system for a “single step”

Overview of Results



Need:

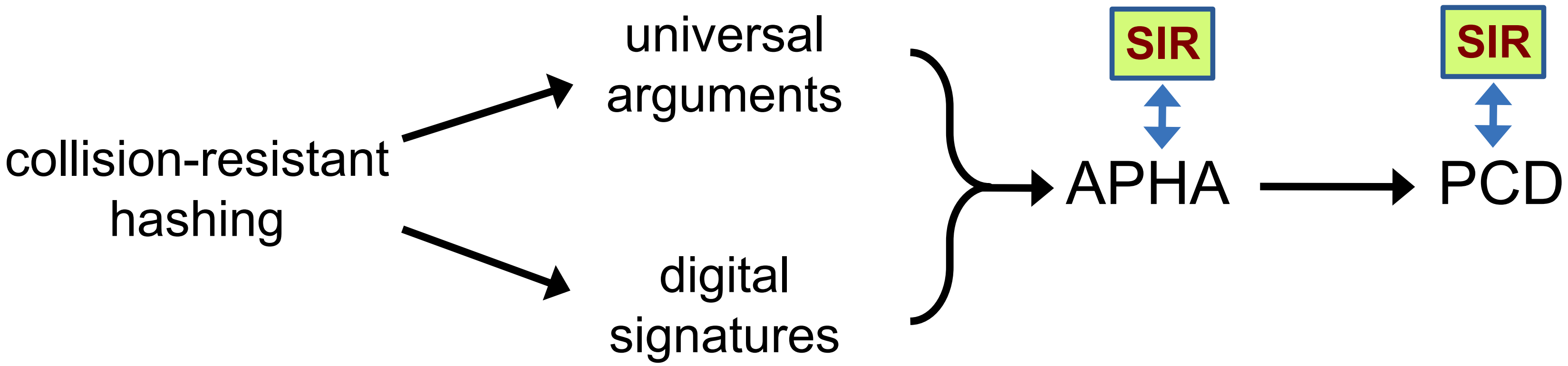
- Universal arguments (CS proofs) that are public-coin and constant-round [Barak Goldreich 02] [Micali 94]
- Signature schemes that are strongly unforgeable

generic (from UOWHFs): [Goldreich 04]

efficient: [Boneh Shen Waters 02]

Both exist if Collision Resistant Hash schemes exist.

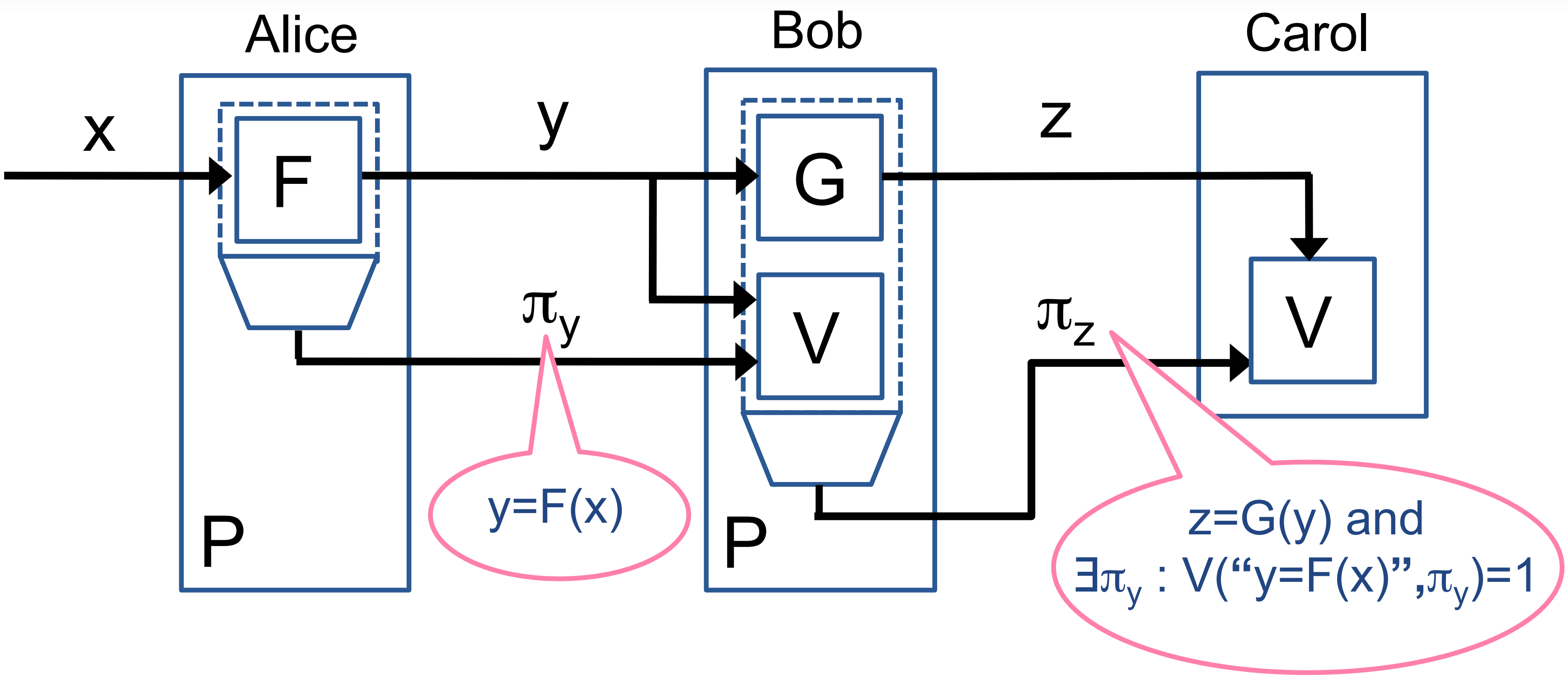
Rest of this talk



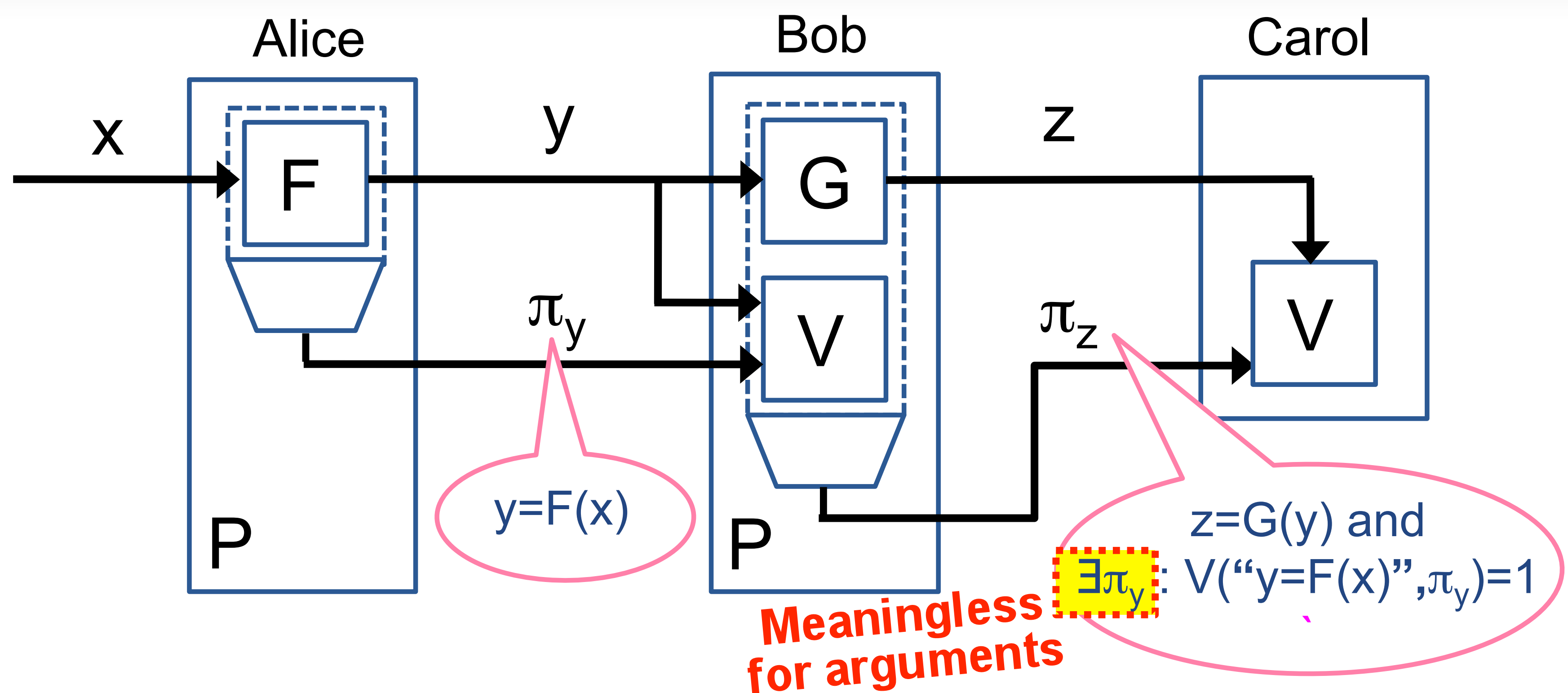
Rest of this talk:

- Intuition on how to aggregate proofs in “F and G” example

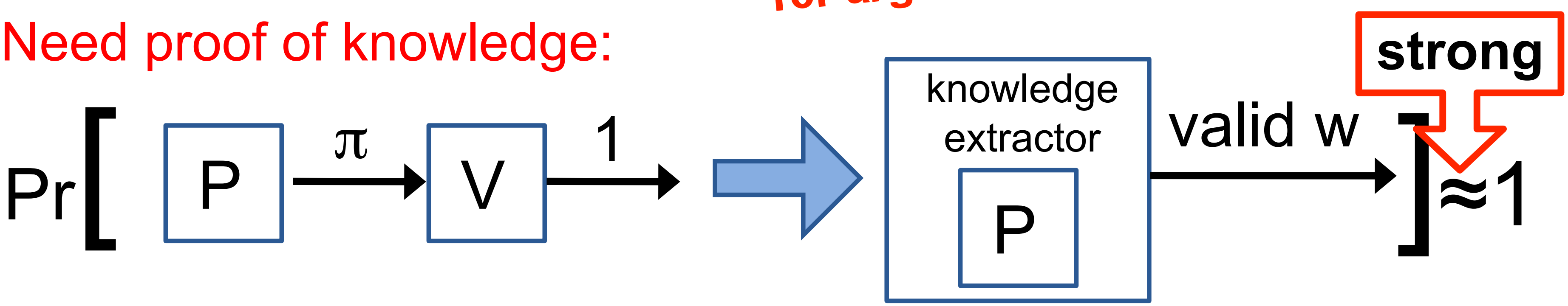
Proof aggregation



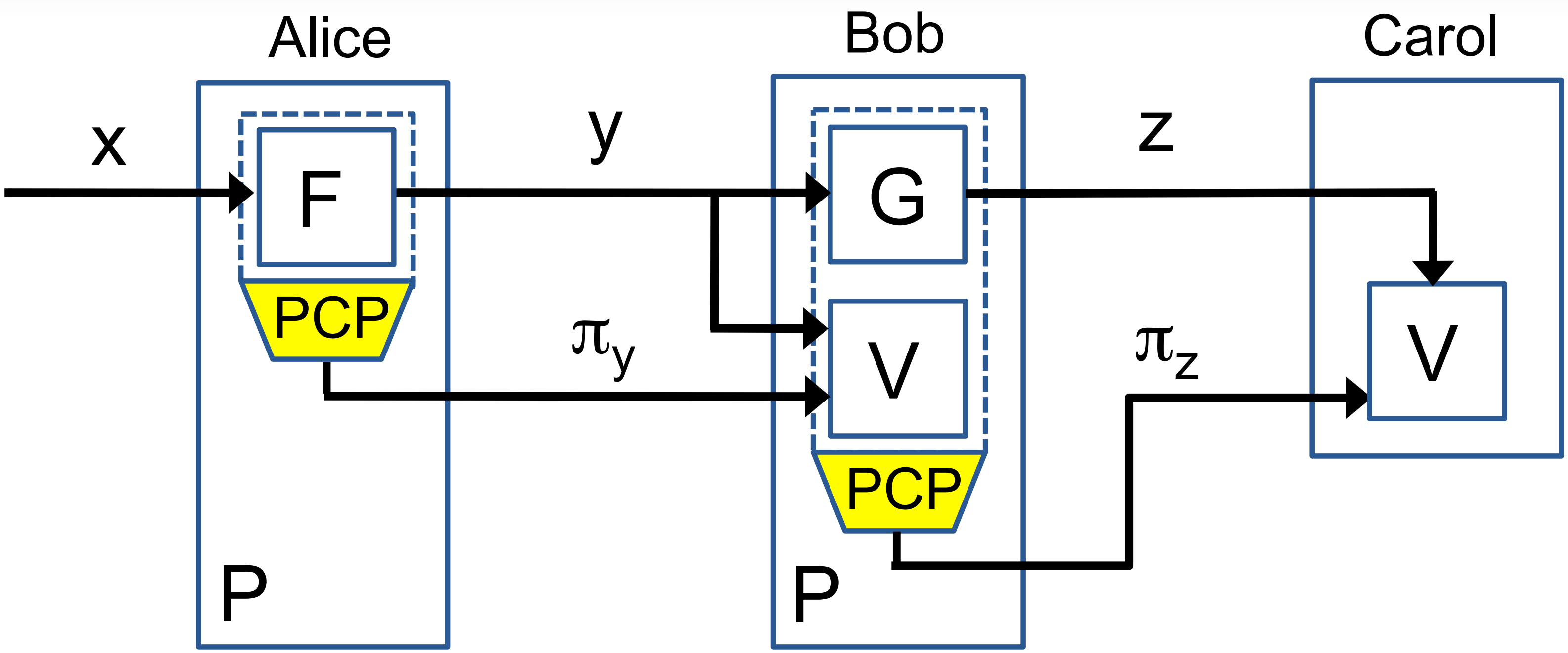
Soundness vs. proof of knowledge



Need proof of knowledge:



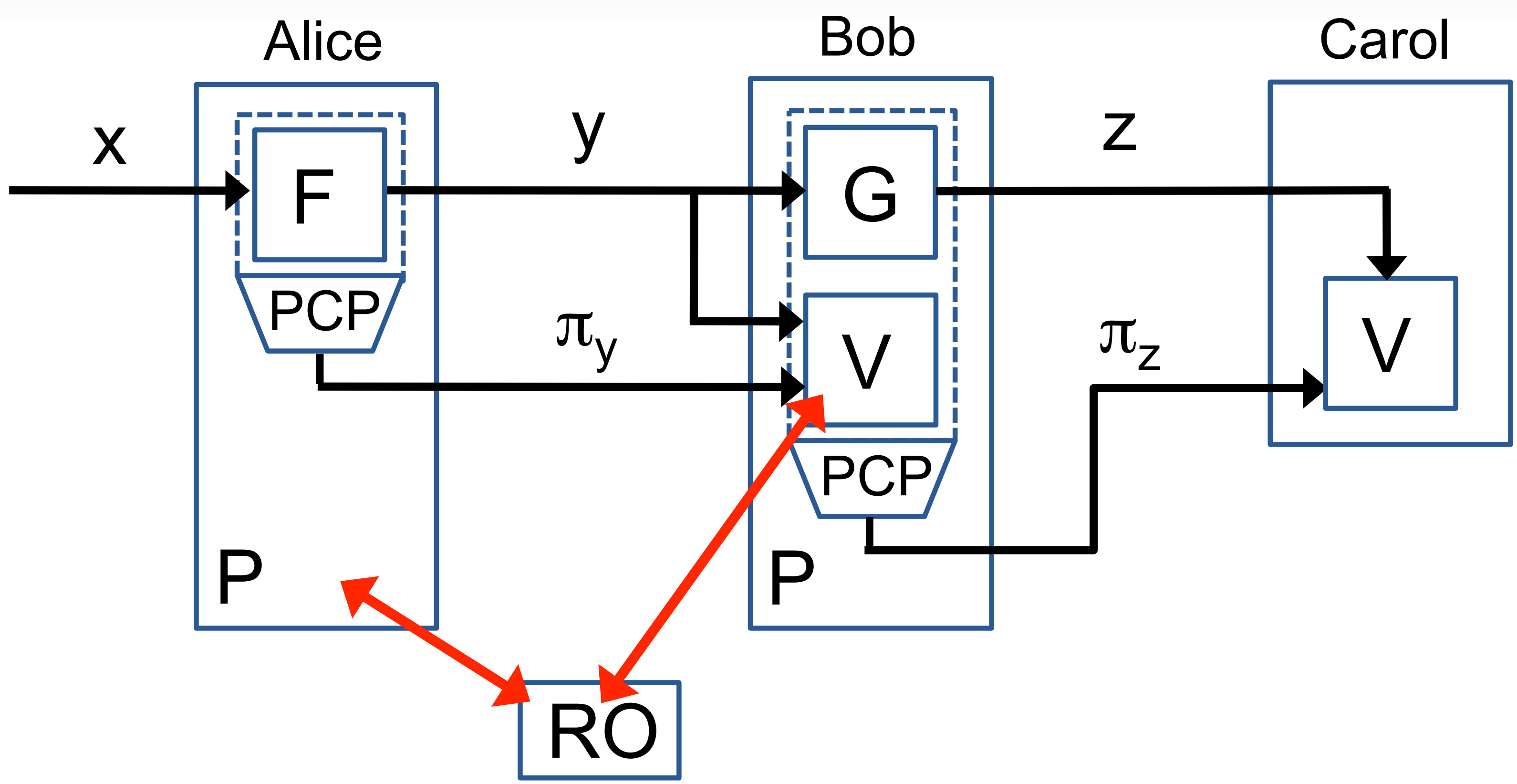
Must use PCPs for compression



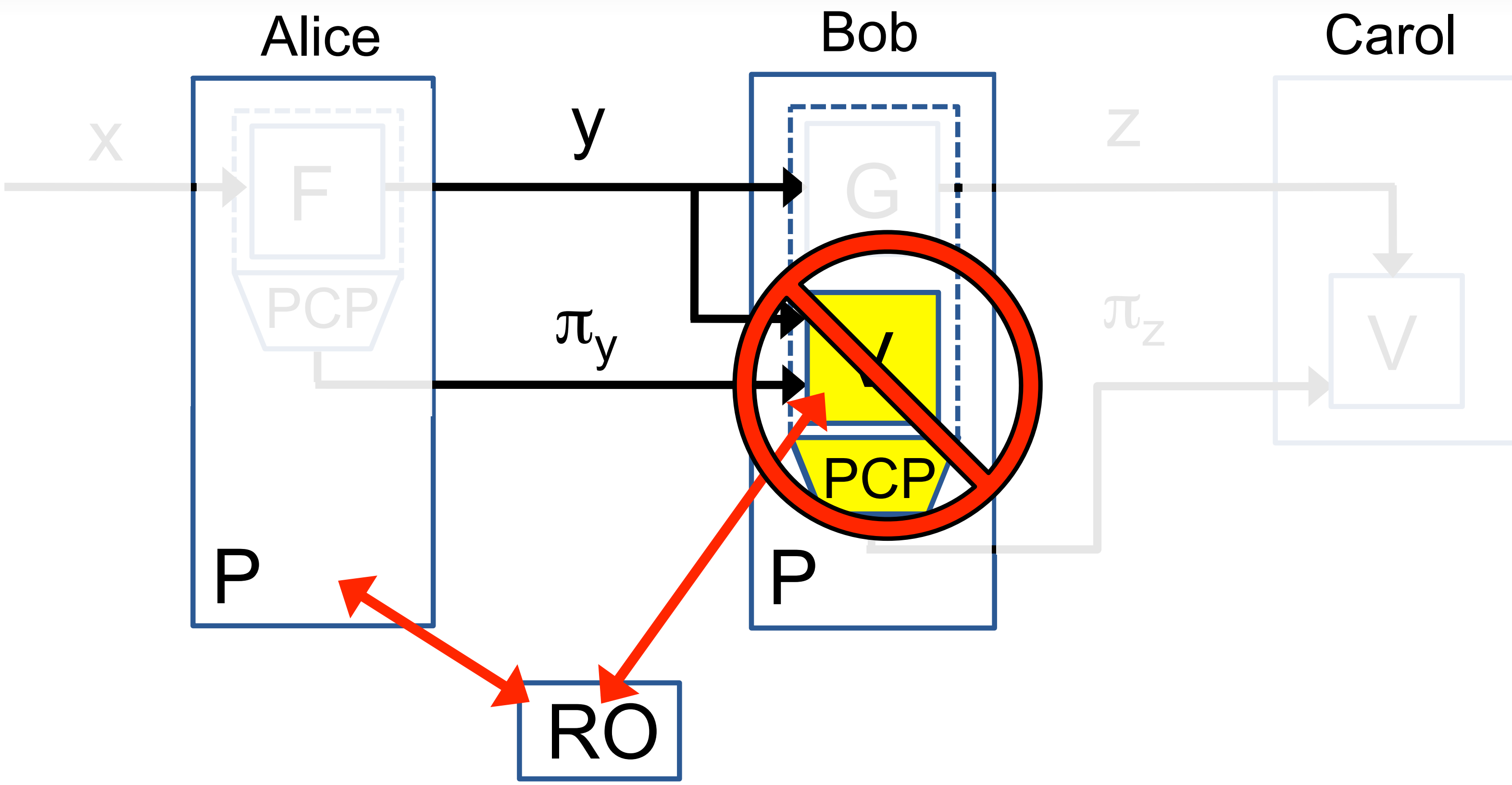
- Probabilistically Checkable Proofs (PCPs) used to generate concise proof strings.

(And there is evidence this is inherent [Rothblum Vadhan 09].)

Must use oracles for non-interactive proof of knowledge

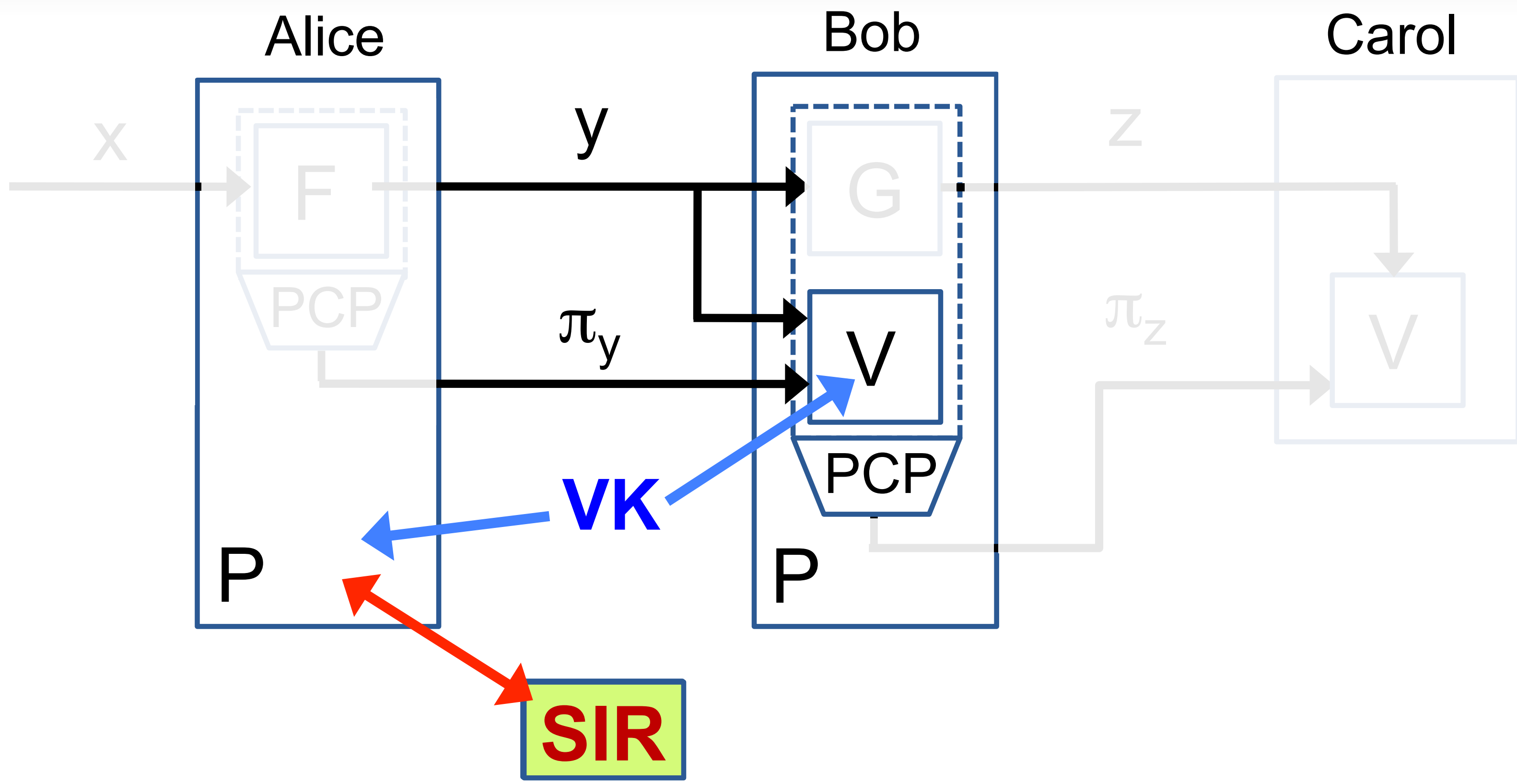


PCP vs. oracles conflict



- PCP theorem does **not** relativize [Fortnow ‘94], not even with respect to a RO [Chang et al. ’92]
- this precluded a satisfying proof of security in [Valiant ‘08]

Our solution:
Public-key crypto to the rescue



Oracle signs answers using public-key signature:

- answers are verifiable without accessing oracle
- asymmetry allows us to break "PCP vs. oracle" conflict, and recursively aggregate proofs

Sketch of remaining constructions

Constructing APHAs:

≈ Fiat-Shamir heuristic

- Start with universal arguments
- De-interactivize by replacing public-coin messages with oracle queries
- Add signature to statement to force witness query (≈ [Chandran et al. 08])
- Prove a very strong PoK by leveraging the weak PoK of UA

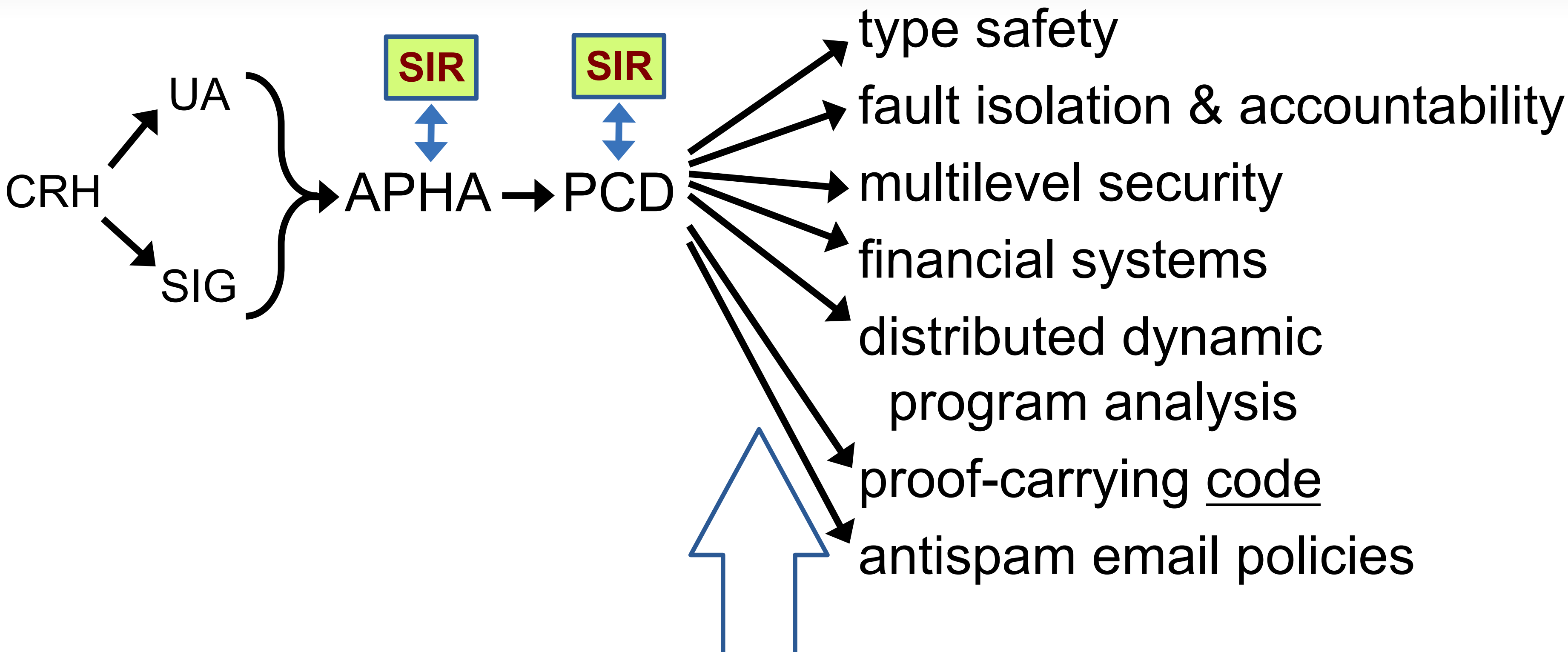
Generalizing to PCD:

- Handle distributed-computation DAG, using APHA for the proofs along each edge.
- **C**-compliance: use fixed aggregation rule to reason about arbitrary computation by proving statements of the form:

C(in,code,out)=1 & "each input carries a valid APHA proof string"

Discussion

Applications



Security design reduces to "**compliance engineering**":
write down a suitable compliance predicate **C**.

Proof-Carrying Data: Conclusions and open problems

Contributions

- Framework for securing distributed computations between parties that are mutually untrusting and potentially faulty, leaky, and malicious.
- Explicit construction, under standard generic assumptions, in a "signature cards" model.
- Suggested applications.

Ongoing and future work

- Reduce requirement for signature cards, or prove necessity.
- Add zero-knowledge constructions.
- Achieve Practicality (PCPs are notorious for "polynomial" overheads).
- Identify and implement applications.

APHA systems

Construction sketch

What we have and what we need

Needed:

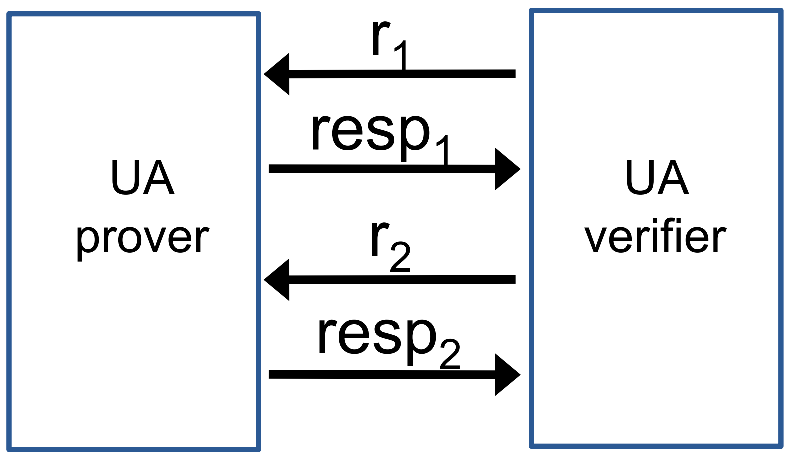
- Highly-compressing non-interactive arguments
- Proof-of-knowledge property that's strong enough to prove "hearsay":
  statements whose truth relies on previous arguments heard from others.
- In the assisted prover model.

We call these
Assisted Prover Hearsay Arguments
(APHA) systems.

Universal arguments

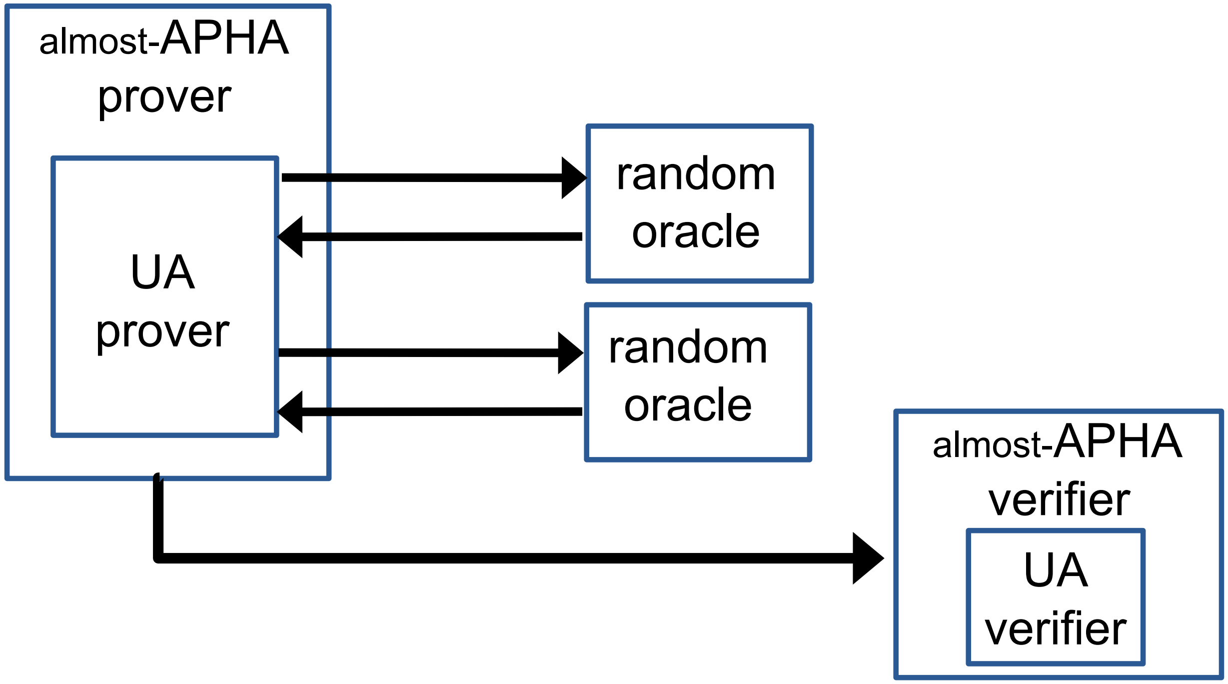
[Barak and Goldreich '02]

Start with universal arguments:
Efficient interactive arguments of knowledge with constant rounds and public coins.



- public coin: r_1 and r_2 are just random coins
- temporal dependence:
  r_2 is sent only after $resp_1$ is received

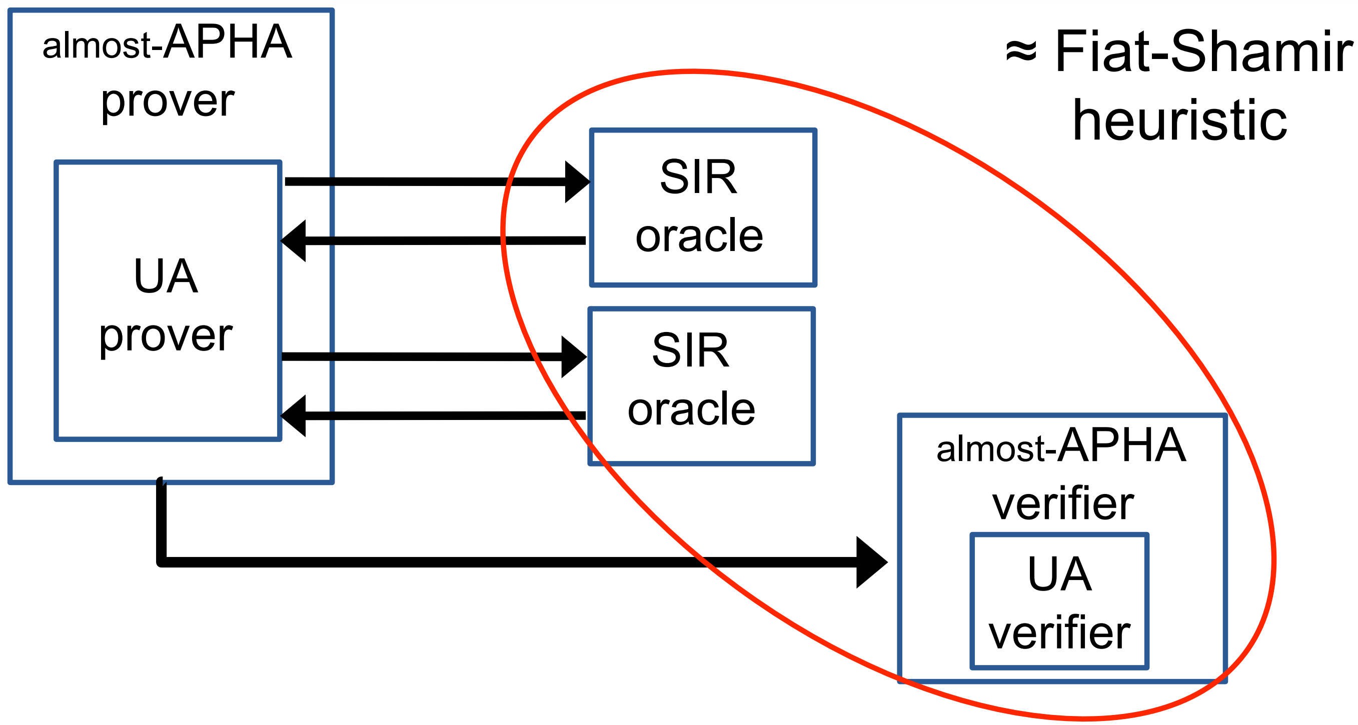
De-interactivize universal arguments: first try



Prover interacts with random oracle, not with verifier:

- obtains signed random strings

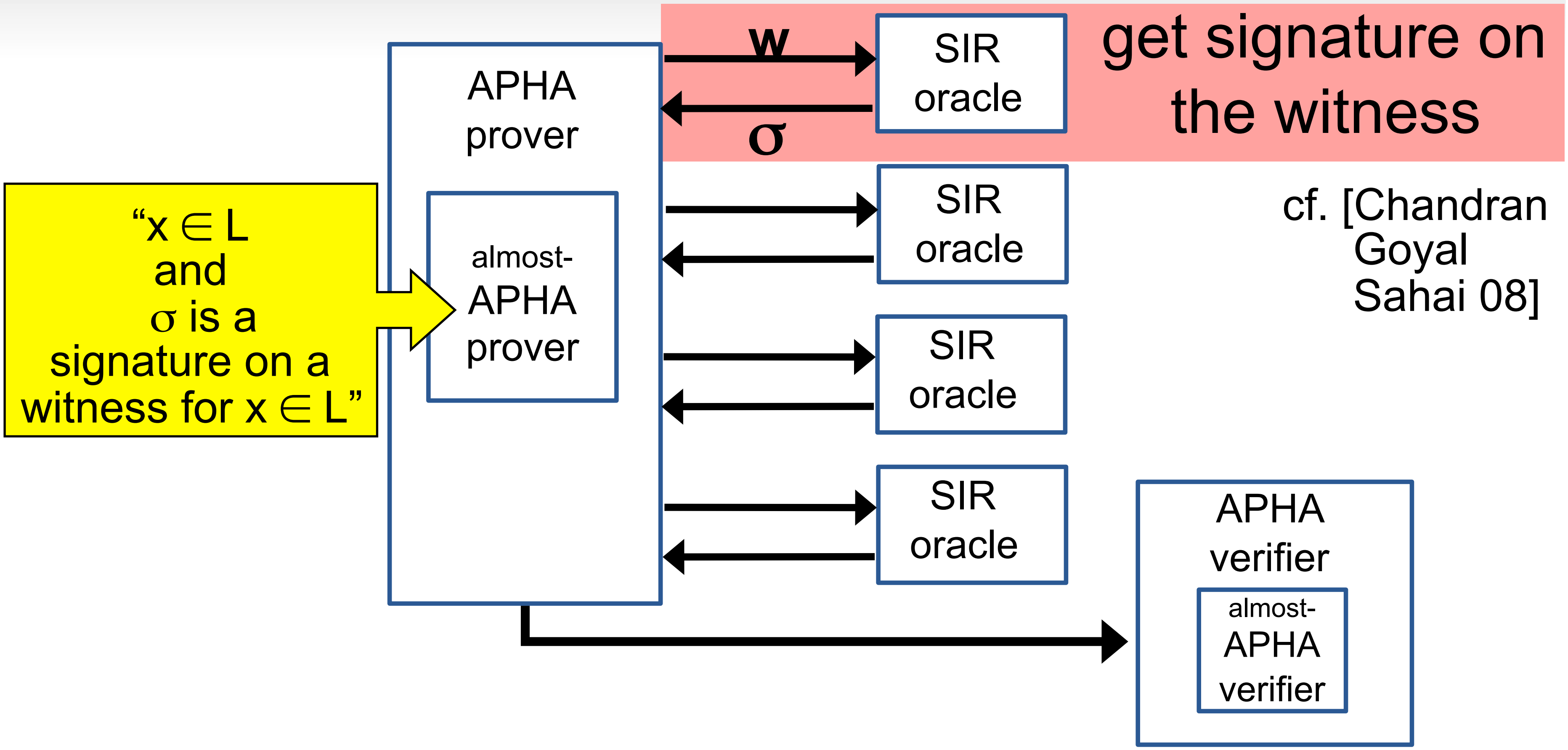
De-interactivize universal arguments



Prover interacts with SIR oracle, not with verifier:

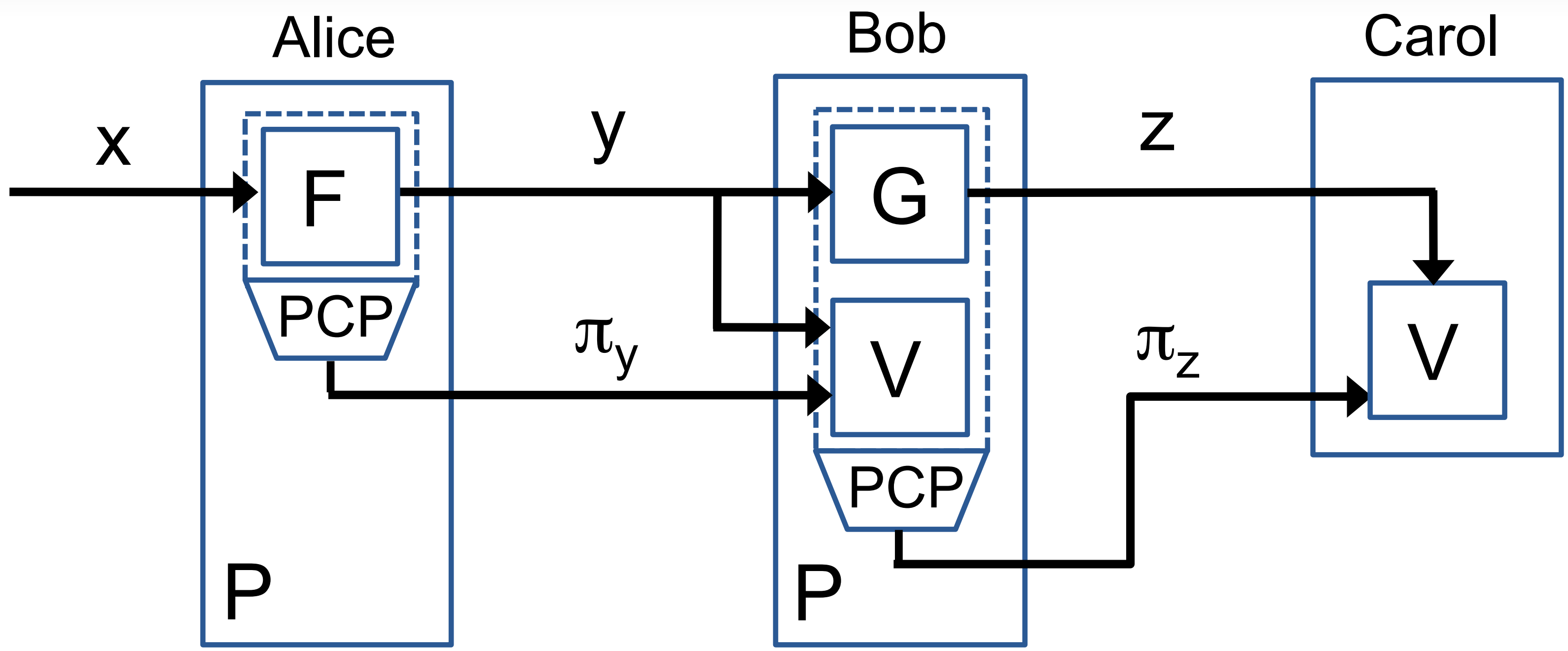
- obtains random strings
- temporal ordering enforced by having each oracle query include the preceding transcript

Enhance proof of knowledge



- Forces prover to get signature on witness
- Knowledge extractor finds witness by examining the queries
  → strong proof of knowledge

Can now do F and G example



We can now do the above example!

... how about proof-carrying data?

PCD systems

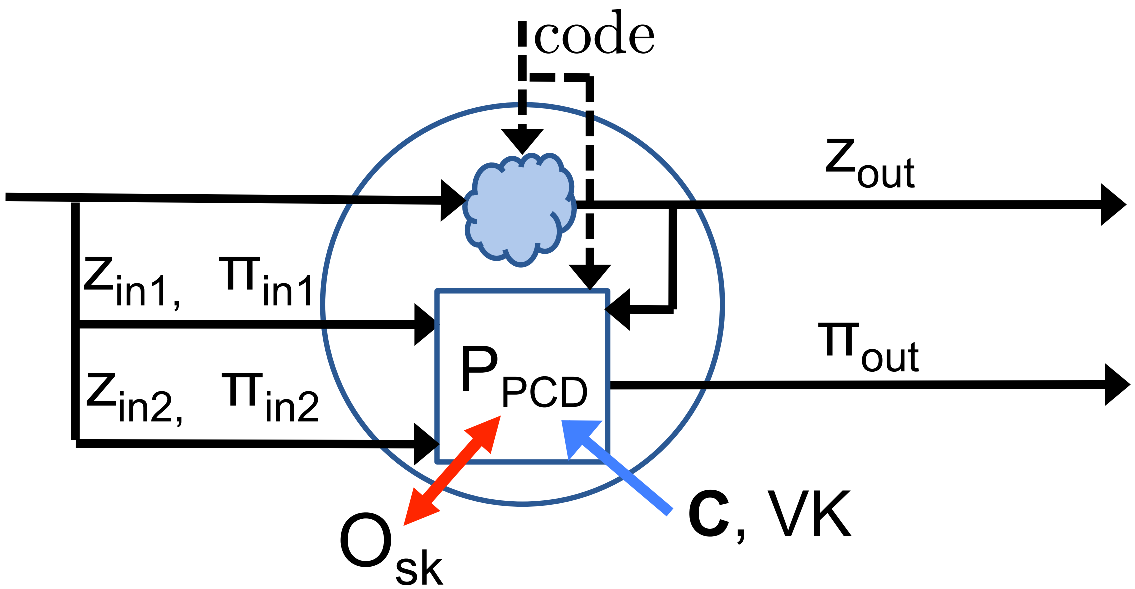
PCD systems

PCD systems are wrappers around APHA systems, with:

- Simpler interface for applications
  (no need to reason about theorems and proofs)
- Simpler proof-of-knowledge property
  (APHAs have a very technical “list extraction” definition)
- **C**-compliance

PCD definition

At every node, a party uses the PCD prover P_{PCD}:



Proofs are checked by the PCD verifier:

V_{PCD}(**C**, VK, z_*, π) decides
if π is a convincing proof for z_*.

PCD definition

PCD systems satisfy

- efficient verifiability:

  $\mathrm{TIME}\big(V_{PCD}(C, VK, z, \pi)\big)$ = polylog(time to make π)

  (actually, much better...)

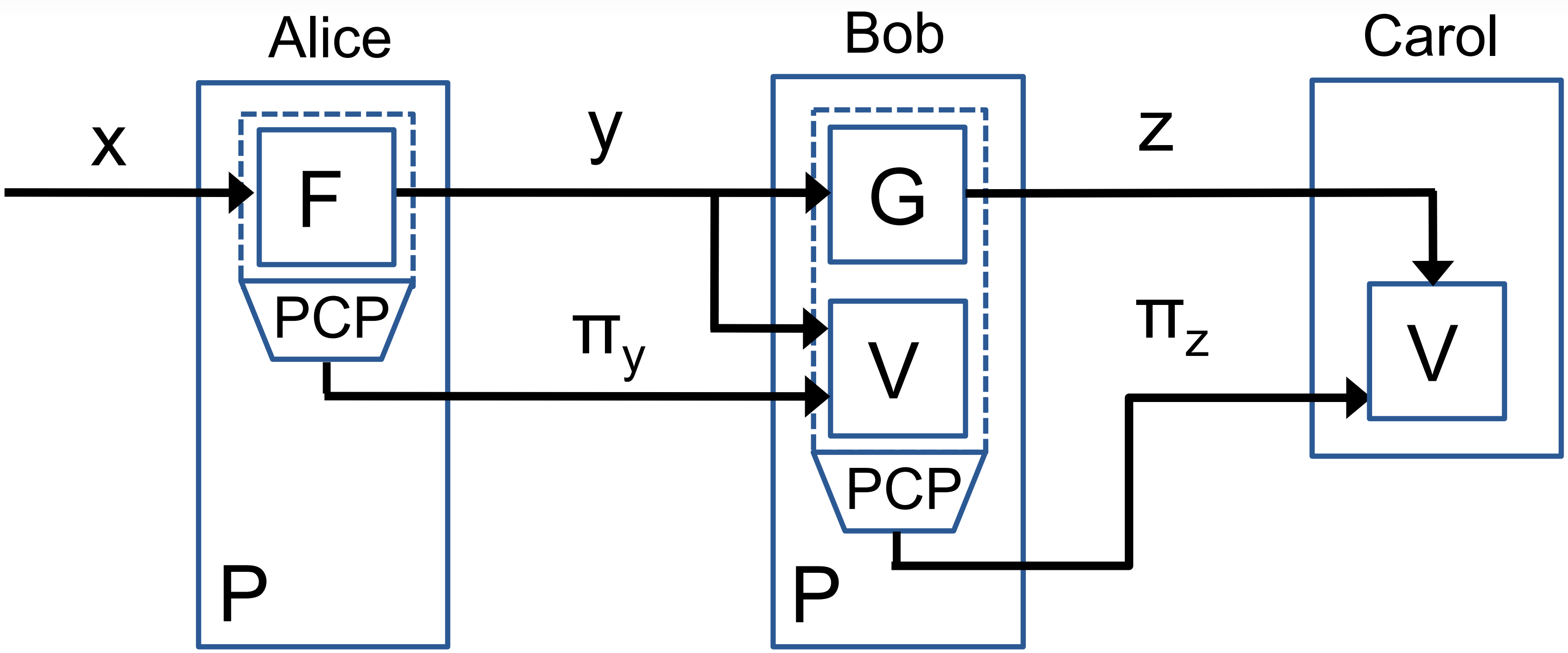
- completeness via a relatively efficient prover:

  if computation is **C**-compliant, then the proof output by prover convinces verifier. Moreover:

  $\mathrm{TIME}\big(P_{PCD}(...)\big)$ = poly(time to check **C**)
  + polylog(time to generate inputs' proofs)

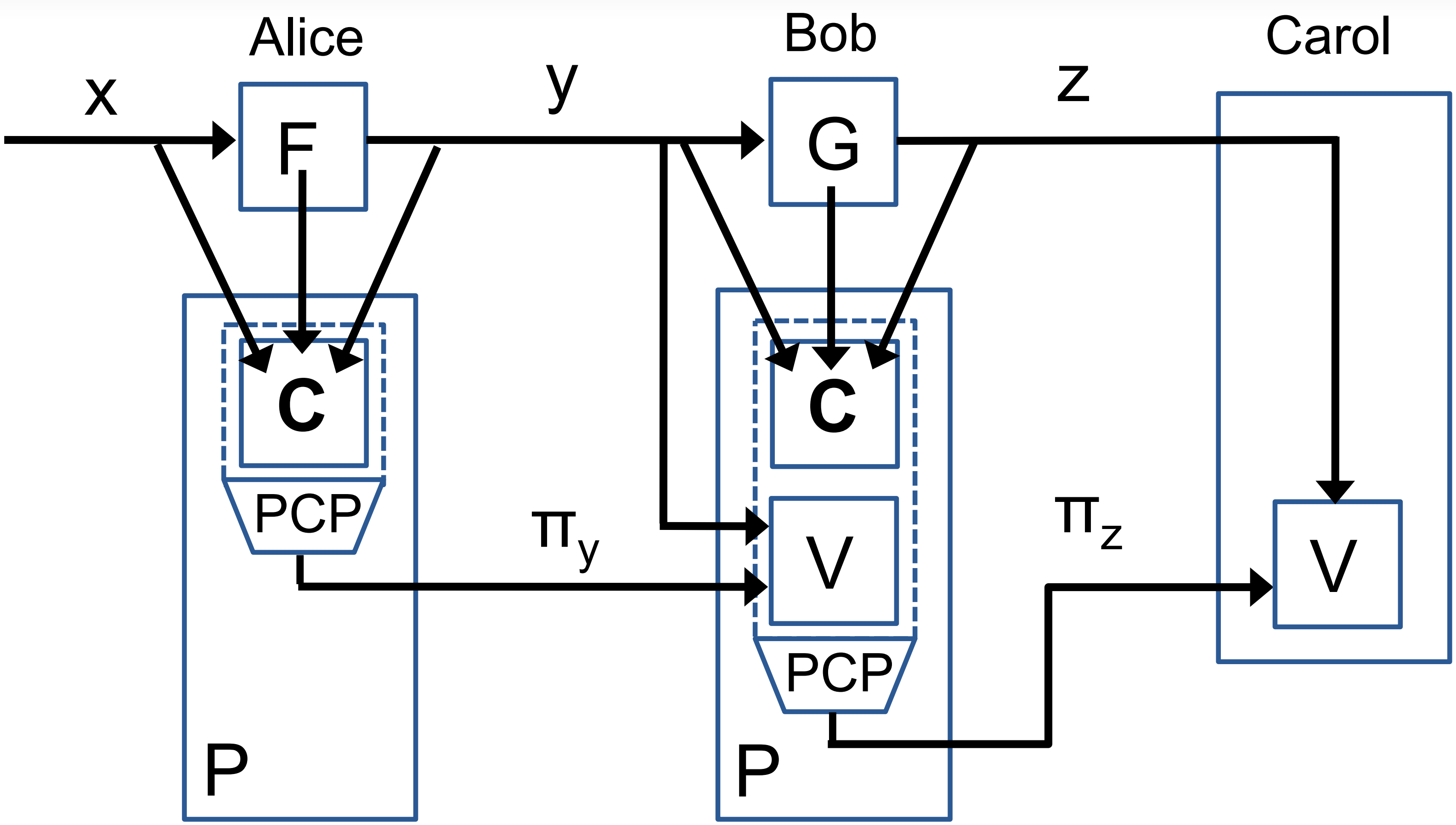
- proof of knowledge: from any convincing prover, can extract a whole **C**-compliant computation

Back to F and G



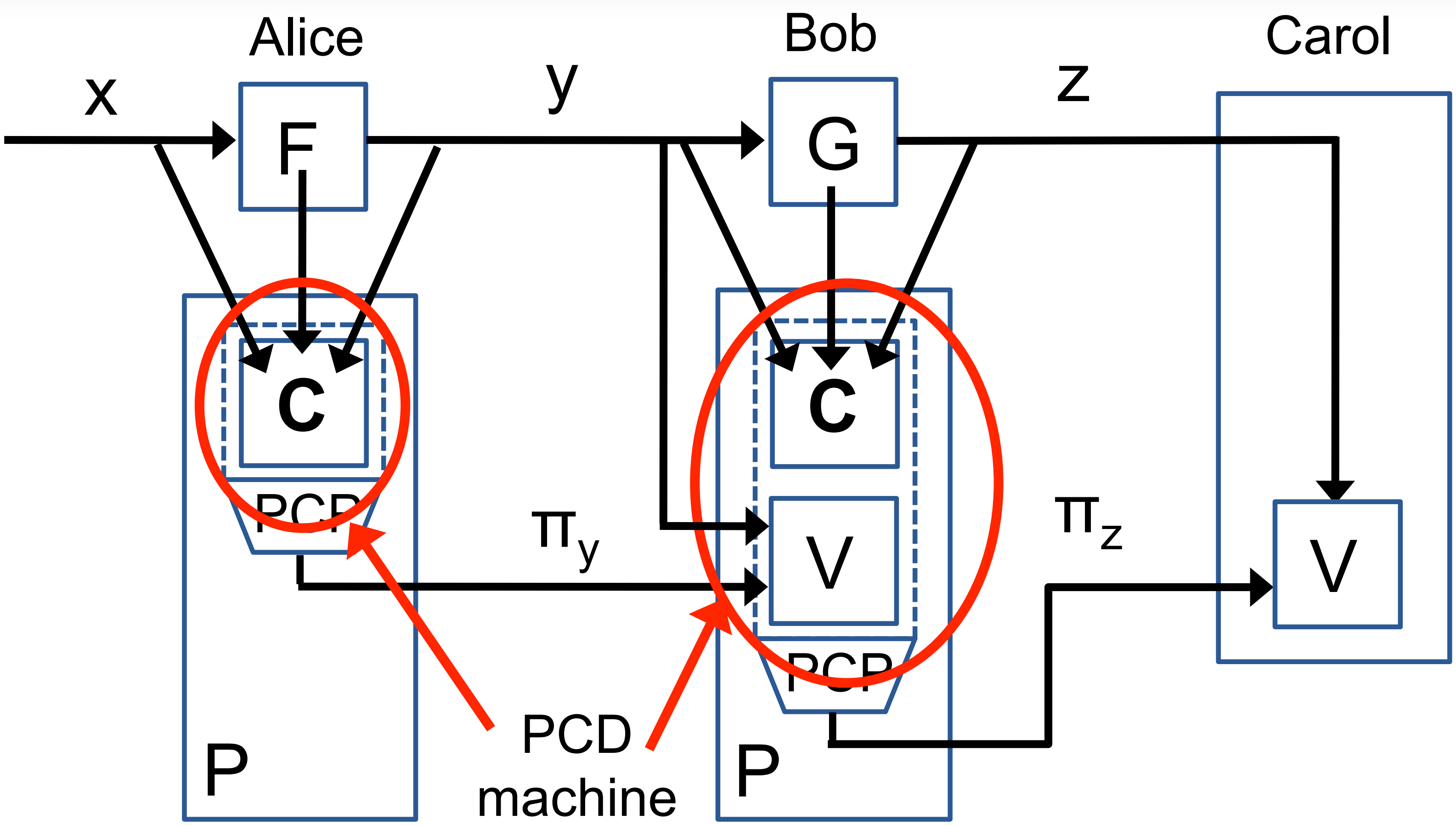
- Having APHA systems, we can already do the above example
- How to generalize to **C**-compliance?

Adding **C**-compliance



- "Export" the choice of computation to be an input to a "fixed rule of aggregation"

PCD Machine



- Such fixed rule we call the PCD machine, and it depends on **C**