Composition of Cryptographic Protocols - Feasibility

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Some slides borrowed from Manoj, Huijia, Abhishek and Rafael

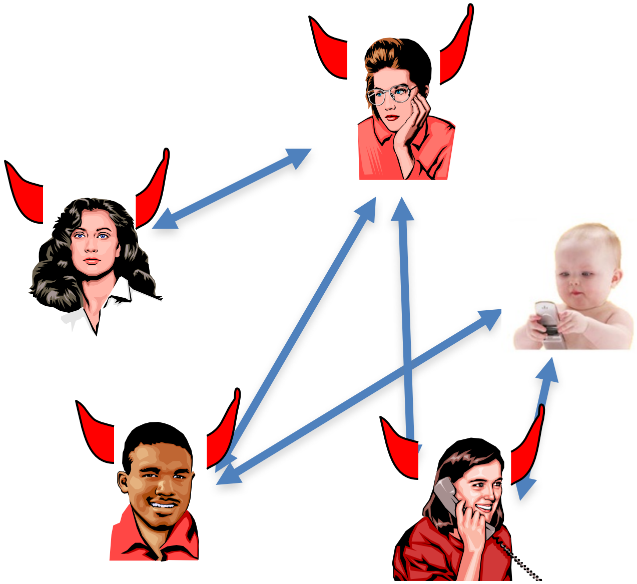
Secure Multi-party Computation
[Yao,Goldreich-Micali-Wigderson]

Goal: Allow a set of distrustful parties to compute any functionality *f* of their inputs, while preserving:

Correctness

Privacy

Even when no honest majority

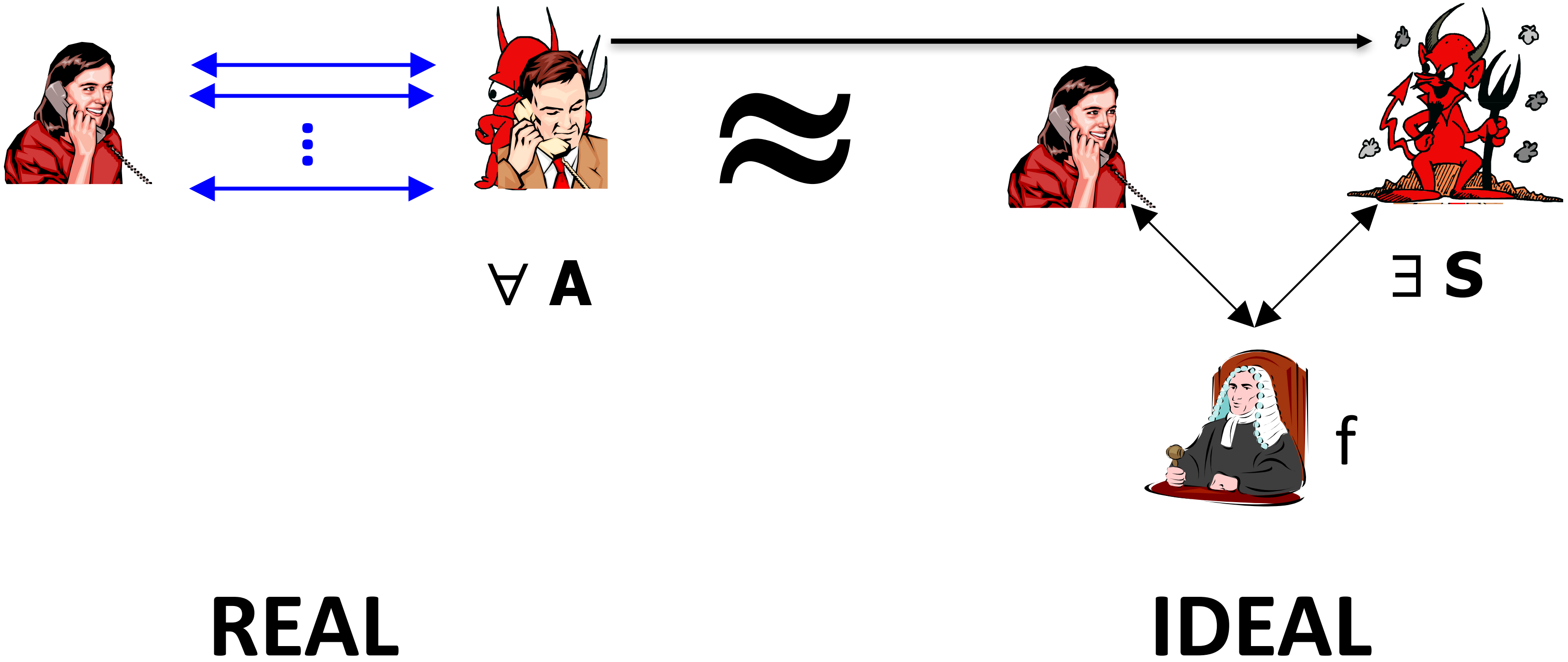


Real World / Ideal World Paradigm

Step 1: Specify goal as an functionality f performed by an ideal trusted service

GOAL = CORRECTNESS + PRIVACY

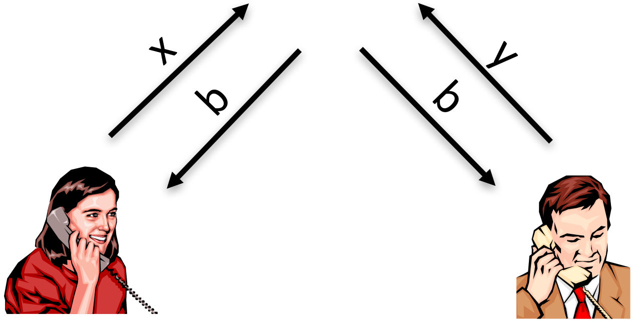
Step 2: Security defined via protocol emulation in ideal world (a.k.a simulation)



Examples of Goals / Functionalities

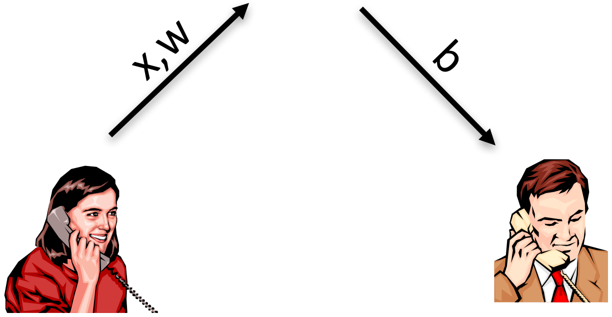
F_{comp}

1. Receive x from A and y from B
2. Output b= (x > y) to A and B



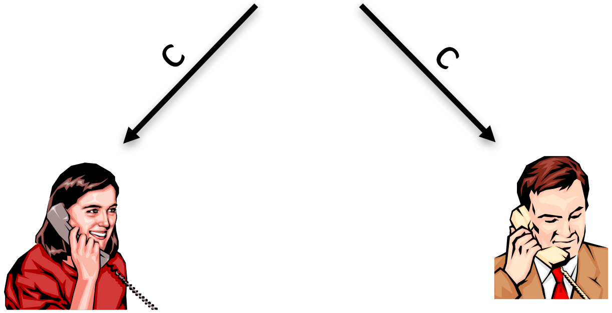
F_{ZK}

1. Receive x,w from A
2. Output b=R(x,w) to B



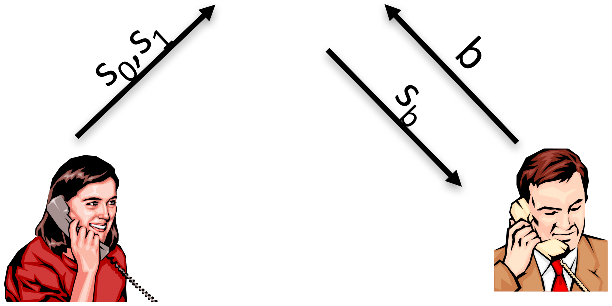
F_{COIN}

1. Toss coin c
2. Output c to A and B



F_{OT}

1. Receive s_0,s_1 from A and b from B
2. Output s_b to B

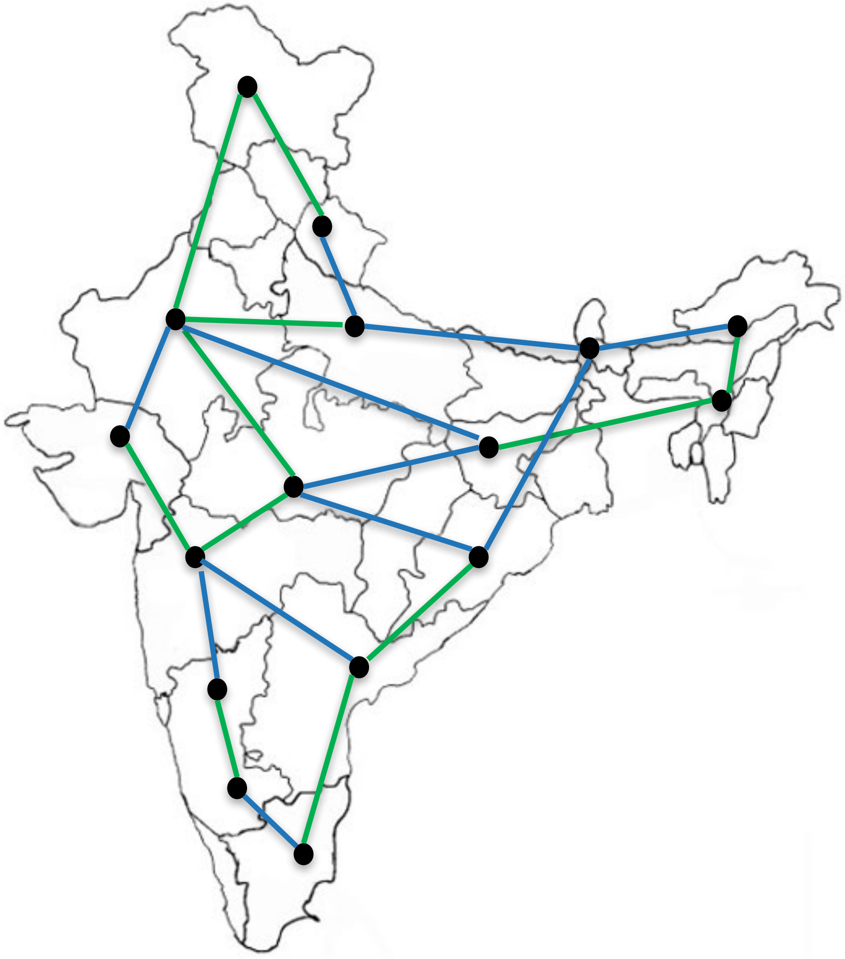


Secure Minimum Spanning Tree [BS,sV]

Goal: Securely compute MST over the union of their edges

Reliance Communication
Anil Dhirubhai Ambani Group

G



airtel

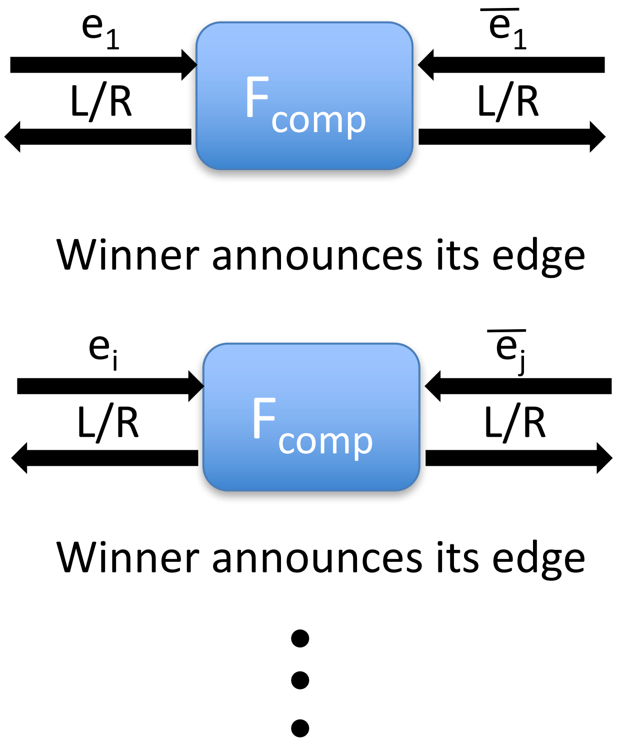
G

Secure Minimum Spanning Tree [BS,sV]

Goal: Securely compute MST over the union of their edges

$G=(V,E_0)$

$e_1,e_2,\ldots,e_{n1}$



e_1 L/R F_{comp} $\overline{e}_1$ L/R

Winner announces its edge

e_i L/R F_{comp} $\overline{e}_j$ L/R

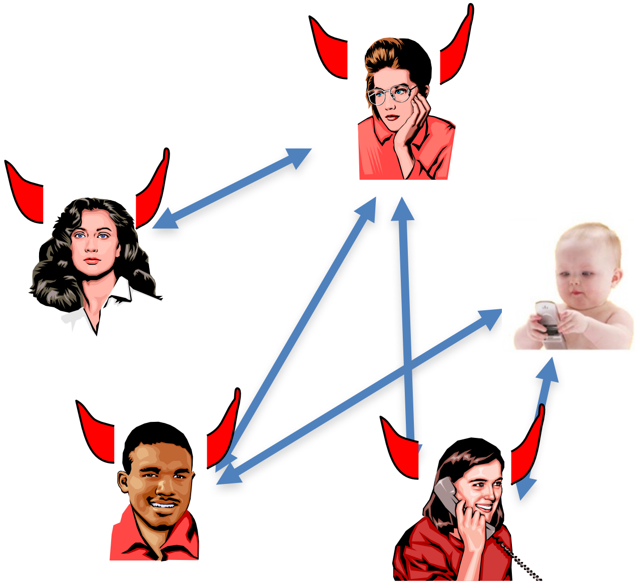
Winner announces its edge

$G=(V,E_1)$

$\overline{e}_1,\overline{e}_2,\ldots,\overline{e}_{n1}$

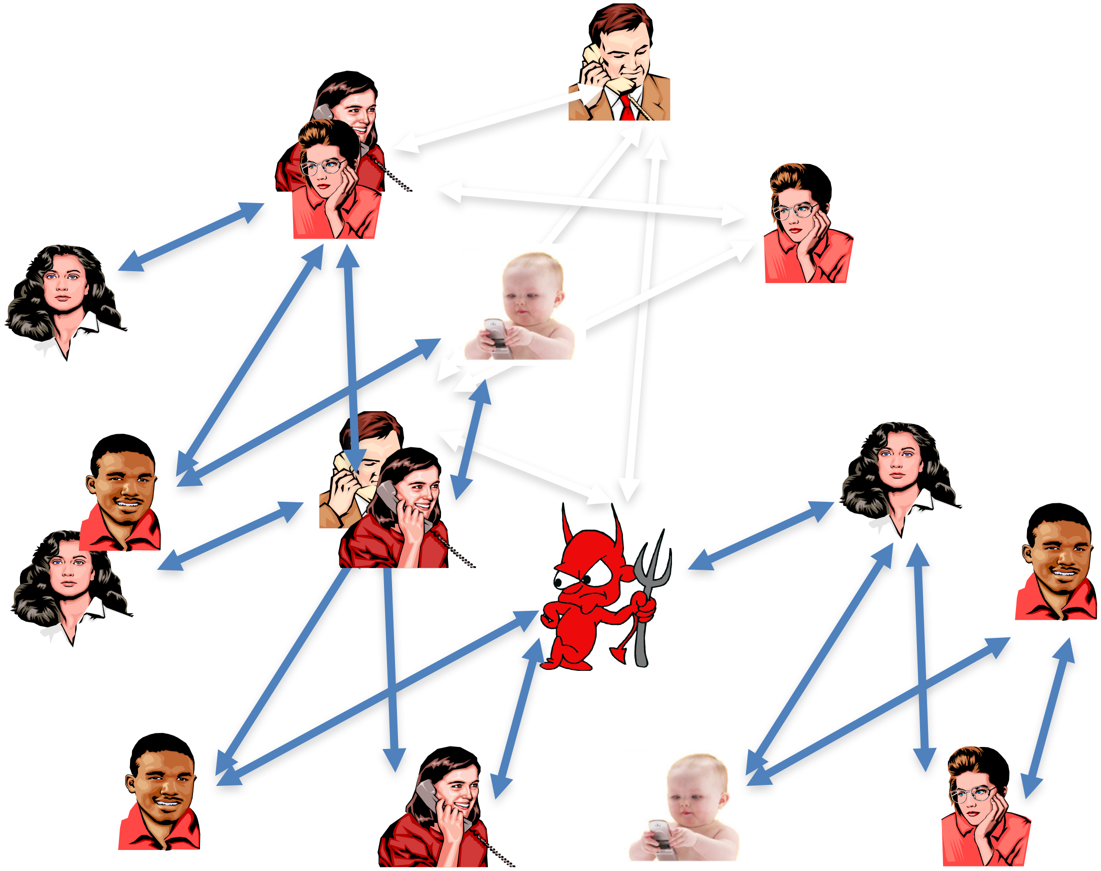
- Suppose, we have secure protocol for F_{comp}
- Replace calls F_{comp} to with secure protocol to get protocol for MST
- Does this mean this new protocol is secure?

The Classic Stand-Alone Model



One set of parties executing a single protocol in isolation

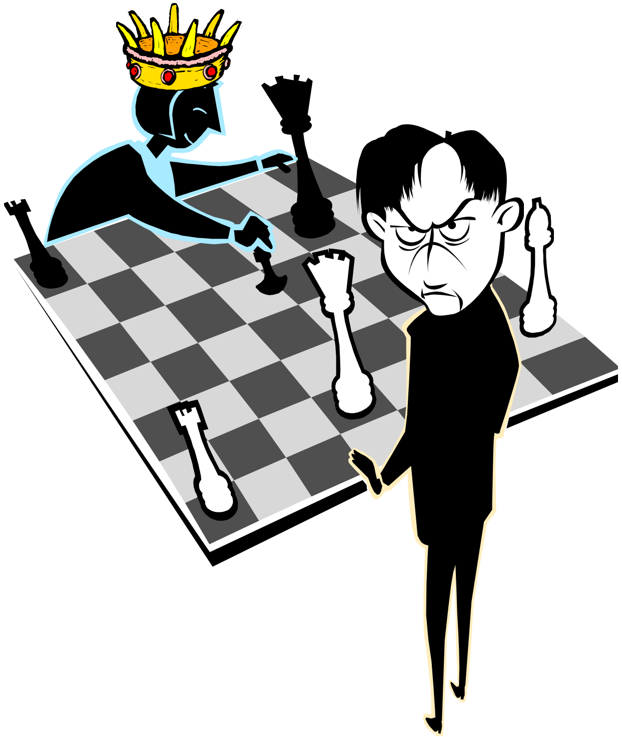
But, Life is CONCURRENT



Many parties running many different protocol executions

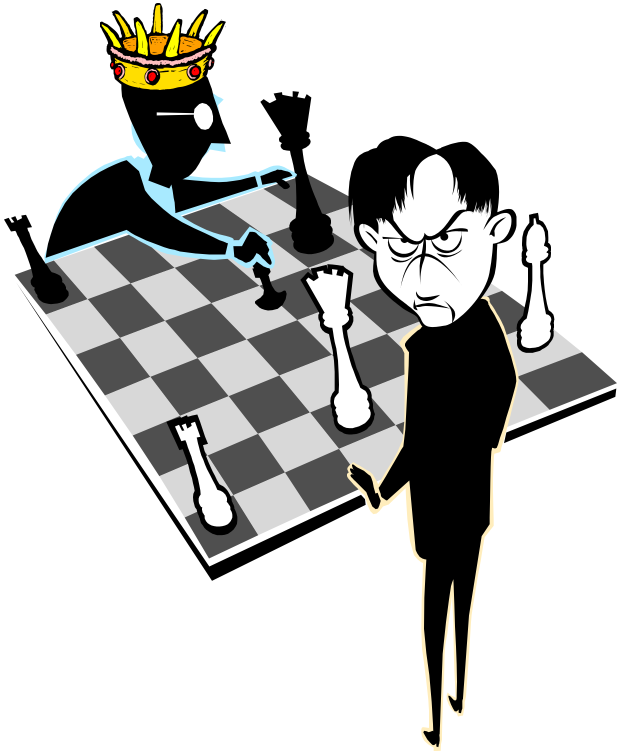
The Chess-master Problem

8am:



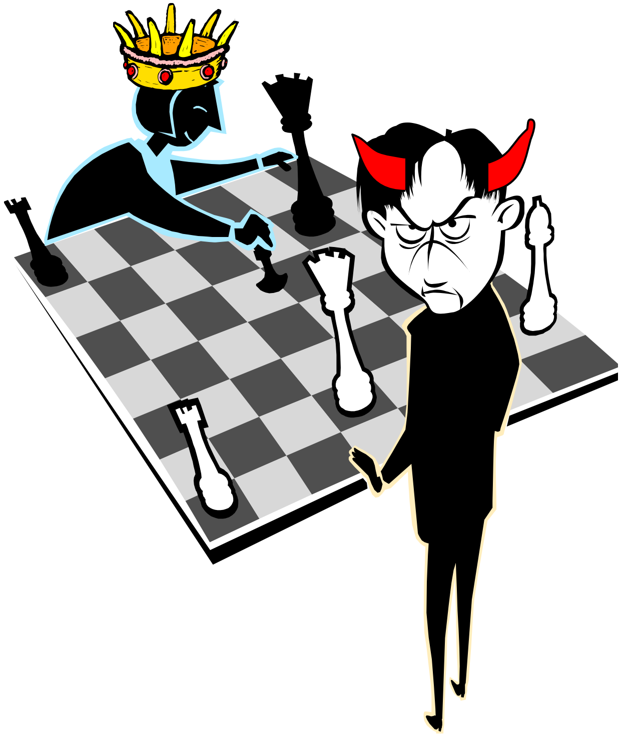
Lose!

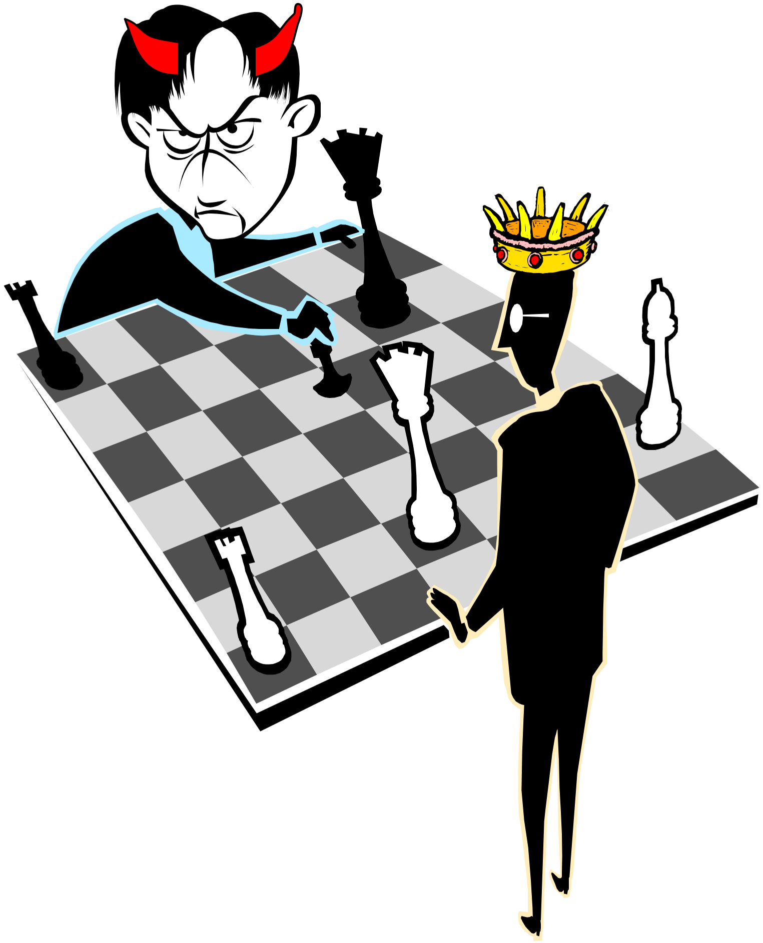
8pm:



Lose!

Win at least 1 (or draw both)

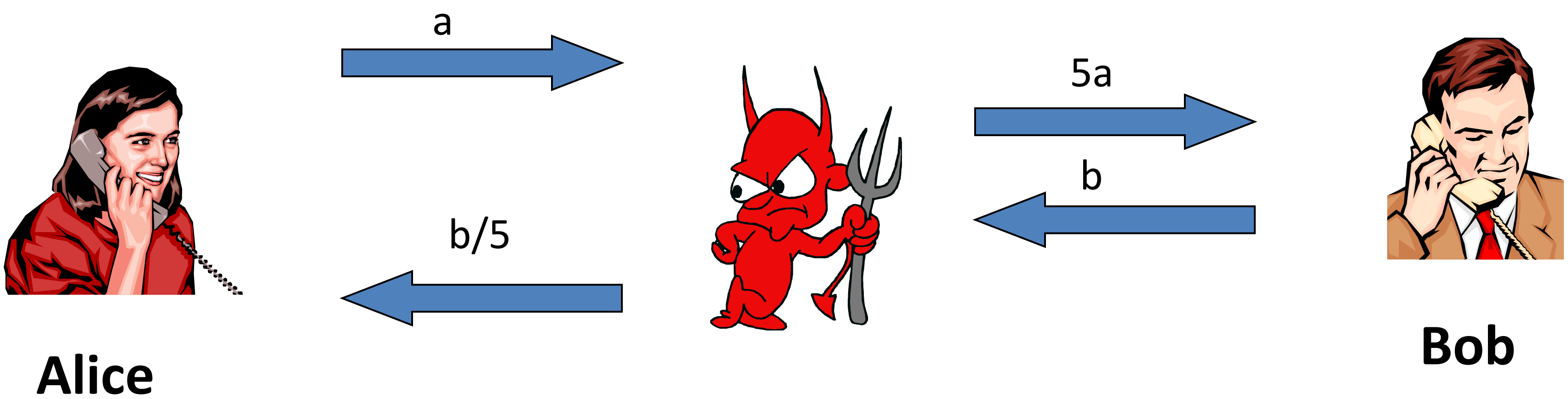




What makes it hard?

- Concurrency
- Scheduling
- Unawarness

Same attack on protocols



a

5a

b

b/5

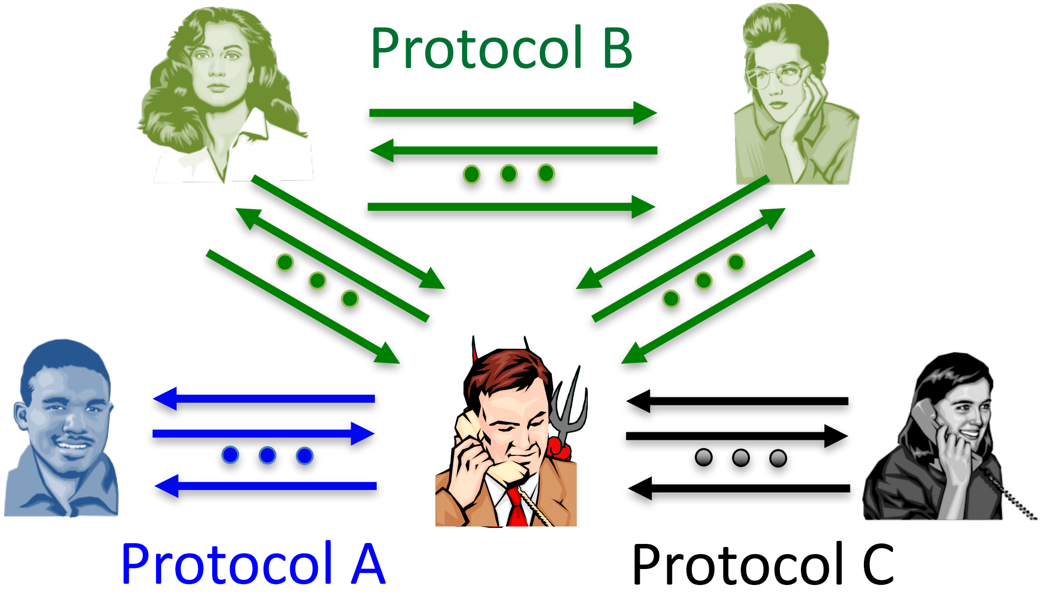
Alice

Bob

E.g., real attacks on OpenSSL implementation [B'98]

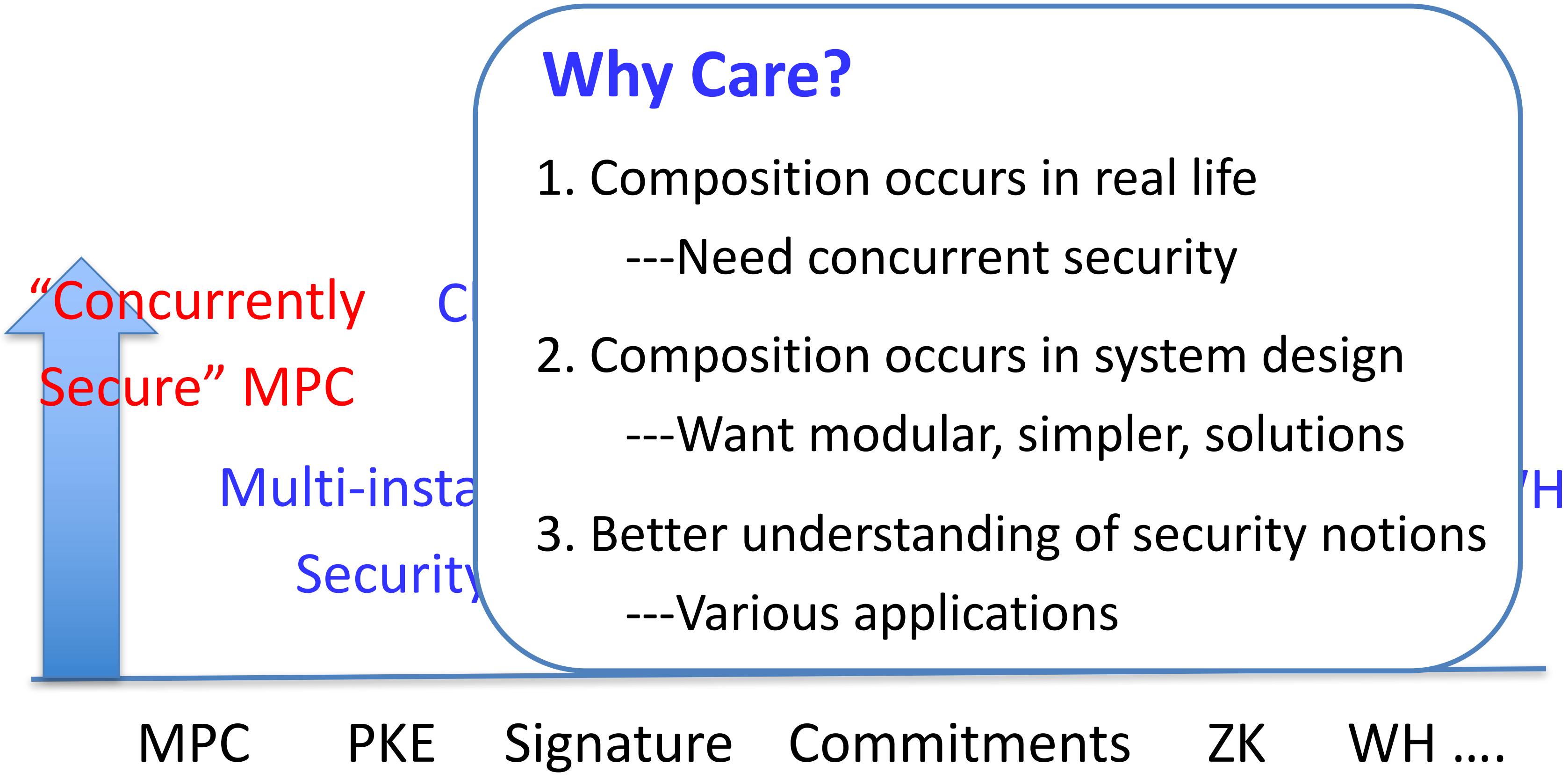
A fundamental question:

Composition



Is security preserved under protocol composition?

Security under composition



Why Care?

1. Composition occurs in real life

   ---Need concurrent security

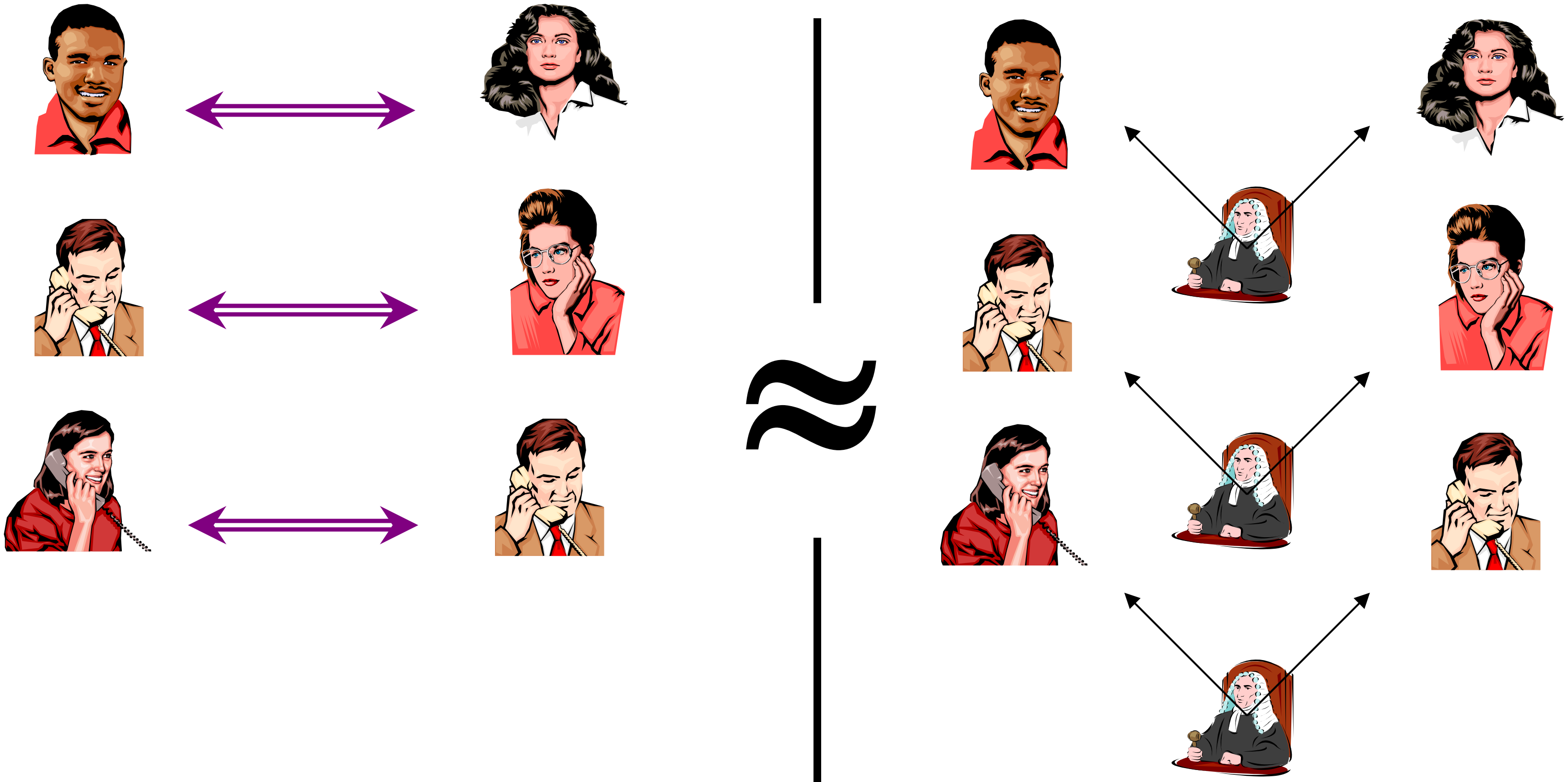
2. Composition occurs in system design

   ---Want modular, simpler, solutions

3. Better understanding of security notions

   ---Various applications

Concurrent Security



Protocol Executions

Trusted party

REAL

IDEAL

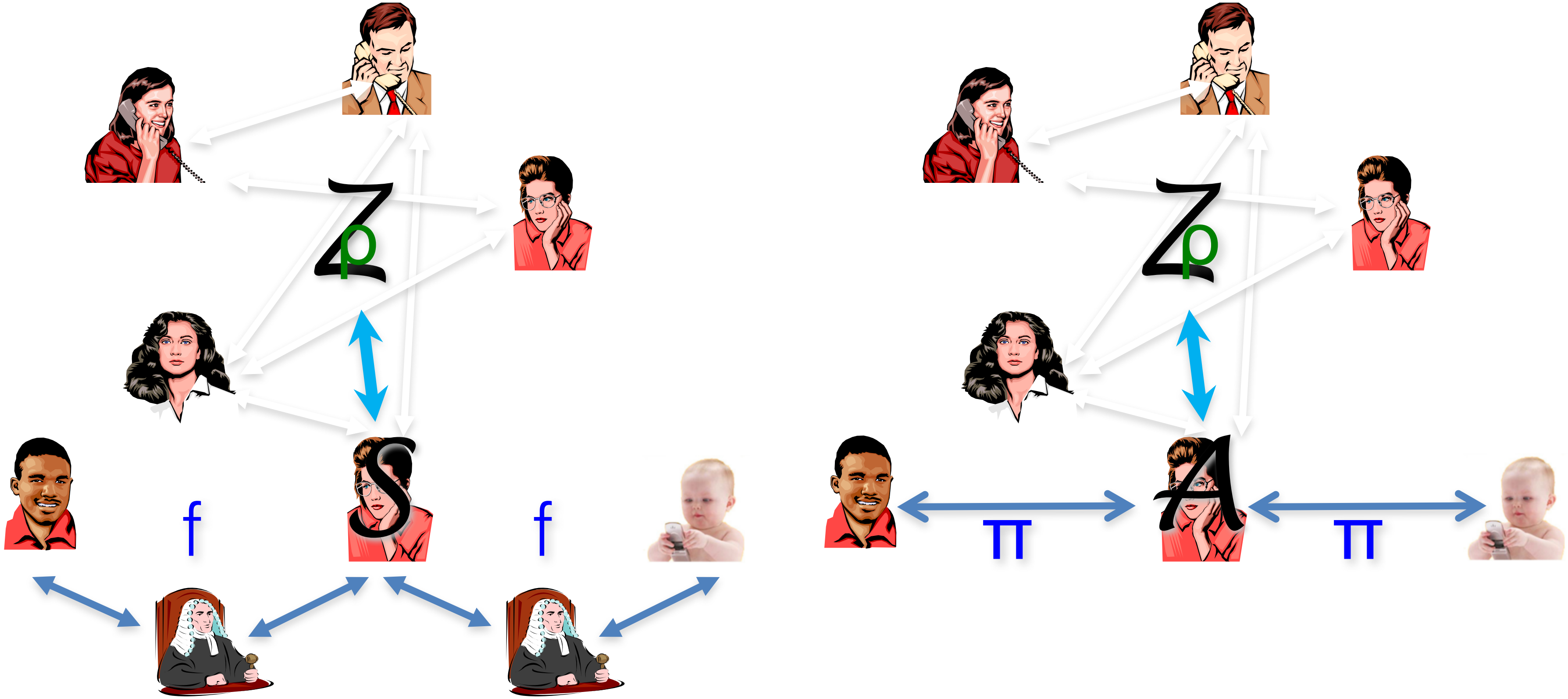
UC Security [C01]

The UC Composition Theorem:

If π UC-implements F_{comp} and

ρ^f UC-implements MST,

then ρ^π UC-implements MST.



UC Security [C01]

The UC Composition Theorem:

If π UC-implements f and
ρ^f UC-implements G,
then ρ^π UC-implements G.

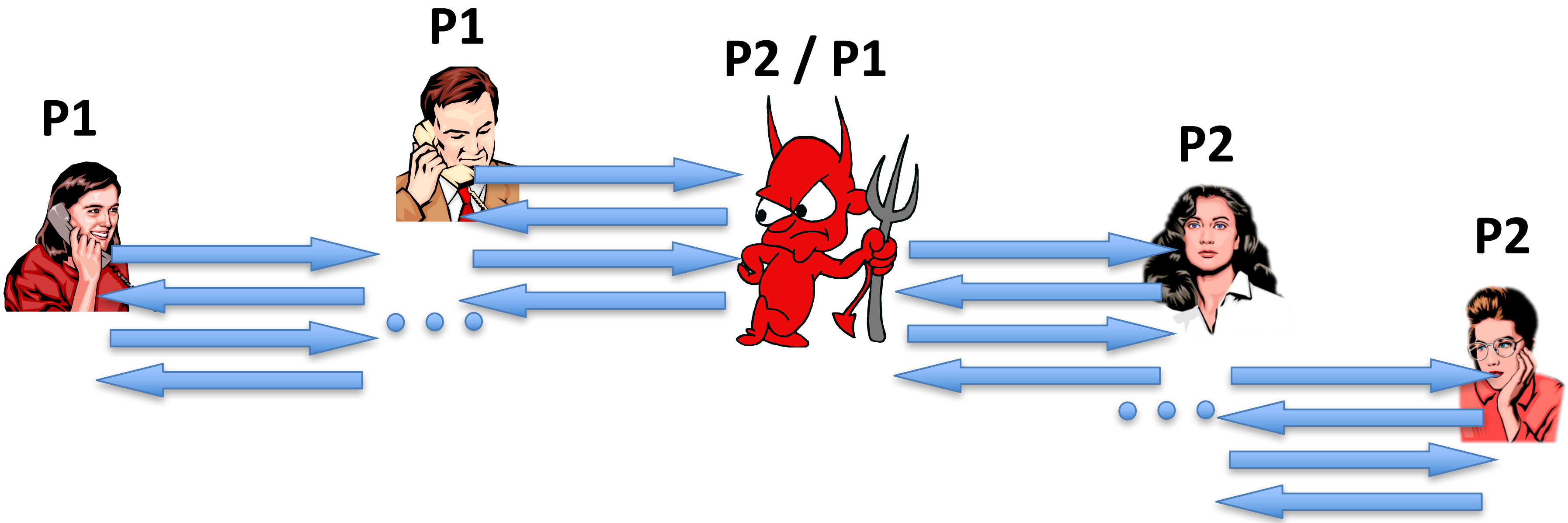
The strongest model of composition

1. Concurrent Security
2. Modular analysis

Theorem [CF, CKL, L]: It is impossible to achieve concurrent security for all "non-trivial functionalities"

mmmmm…Nothing!

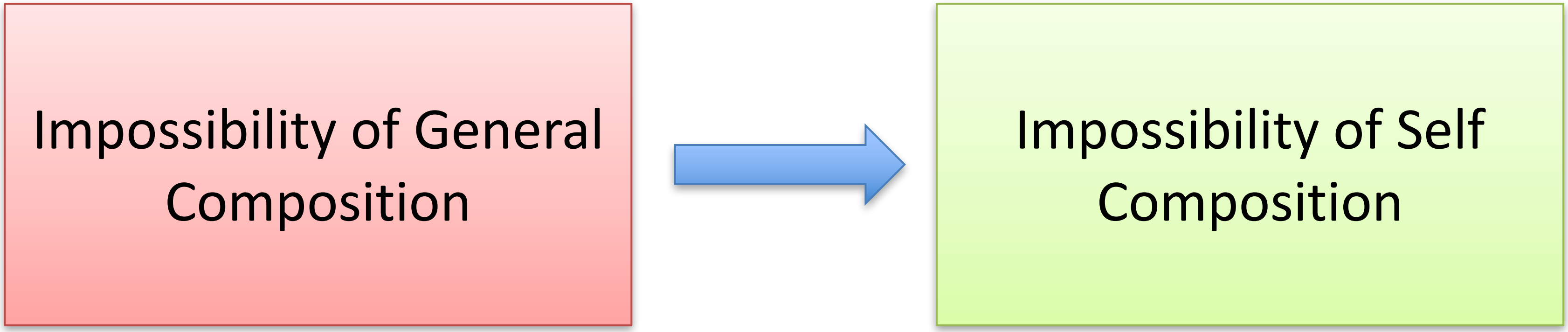
Self-Composition



An unbounded number of instances of the **same** protocol

Examples: Self-Composable MPC ….
Non-Malleable Encryption
Concurrent Non-Malleable (NM) ZK
CMA-secure signature
Password authenticated key exchange (PAKE)

Impossibility Results



Impossibility of General Composition

Impossibility of Self Composition

Chosen Protocol Attack for OT

[BPS06,AGJPS12,GKOV12]

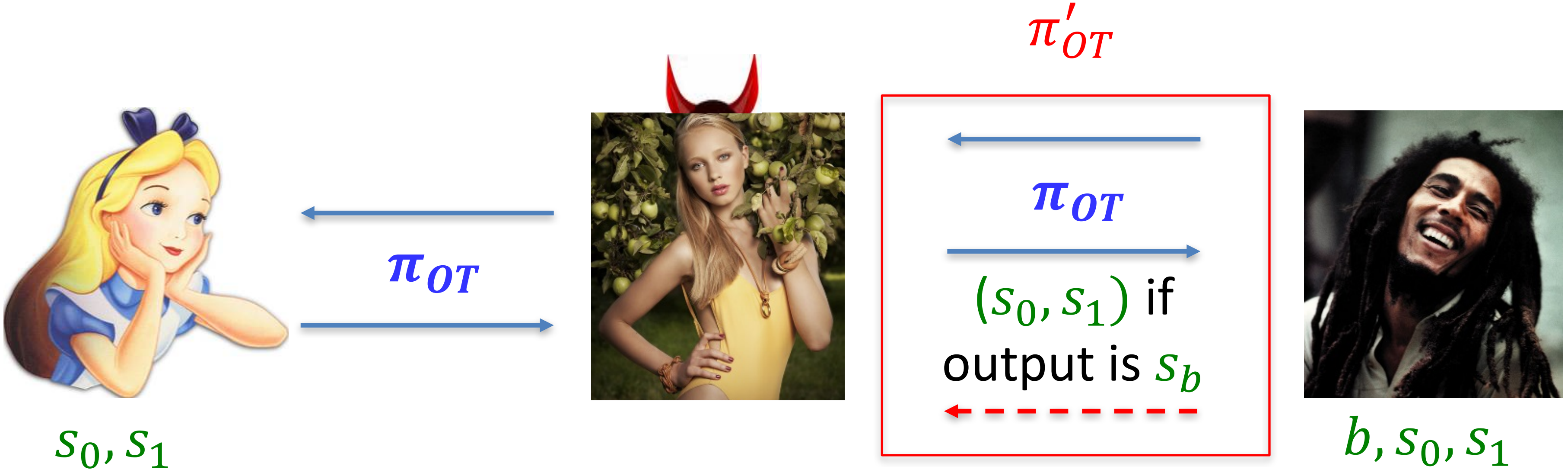
input (s_0 ,

Real Adv can learn honest party's input, but Simulator cannot

Impossibility of General position:

For every π_{OT}, there exist π'_{OT} such that $\pi_{OT} \circ \pi'_{OT}$ breaks security of π_{OT}

Chosen Protocol Attack: Real World



s_0, s_1

π_{OT}

π'_{OT}

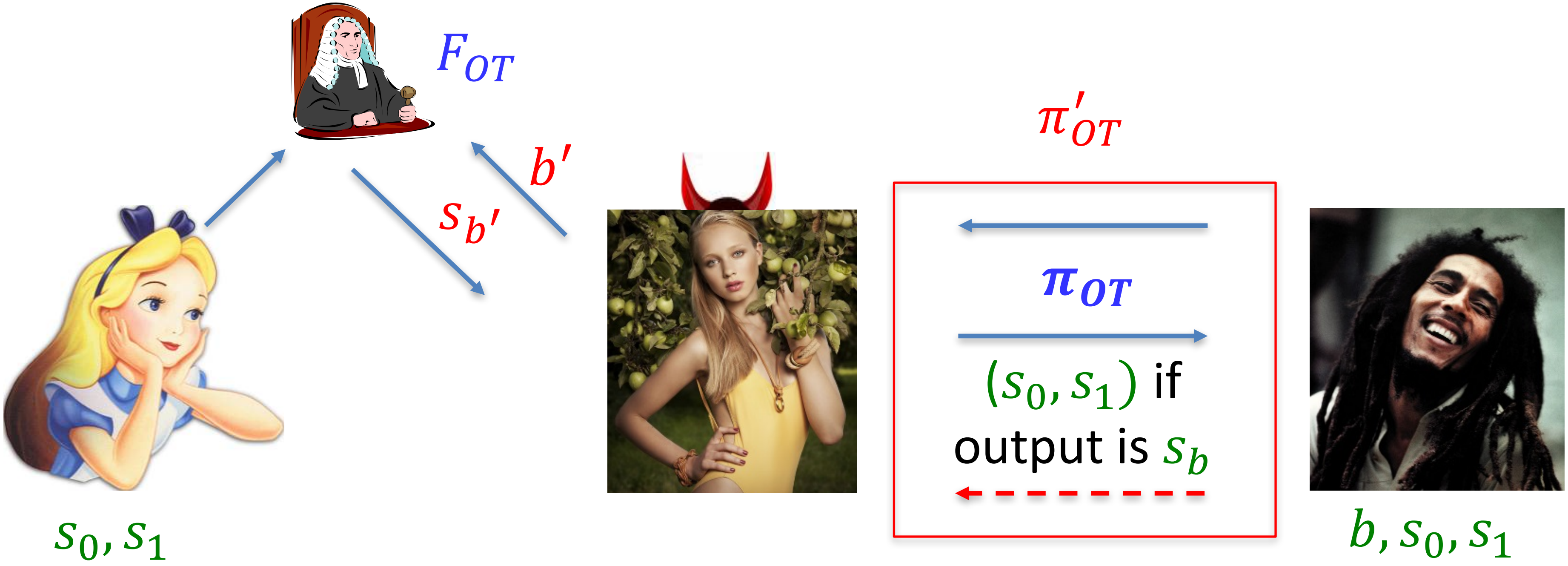
π_{OT}

(s_0, s_1) if output is s_b

b, s_0, s_1

Attack: Eve plays man-in-the-middle to learn (s_0, s_1)

Chosen Protocol Attack: Ideal World



F_{OT}

b'

$s_{b'}$

π'_{OT}

π_{OT}

(s_0, s_1) if output is s_b

s_0, s_1

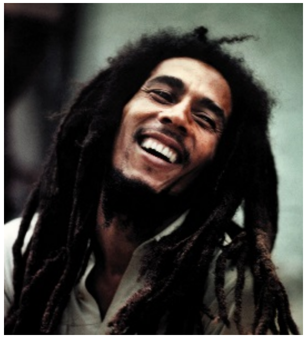
b, s_0, s_1

Attack Fails: With probability $\approx \frac{1}{2}$, Eve will ask for $\boldsymbol{s_{1-b}}$

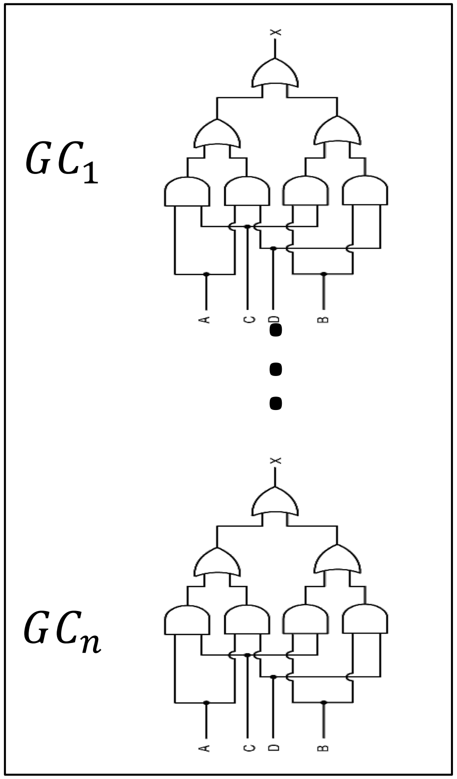
From Impossibility of General Composition to Impossibility of Self-Composition

Want: Multiple Executions of π_{OT} *only* (no π'_{OT})

Replace



with Garbled Circuits computing his Next-Message Functions



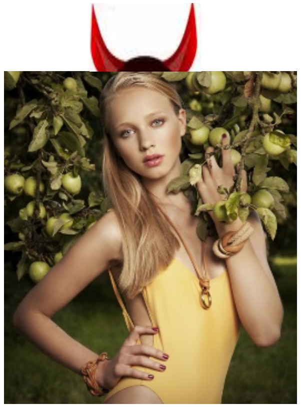
Give Garbled Circuits to Eve as Aux. Input

Problem: Who gets the GC Keys?

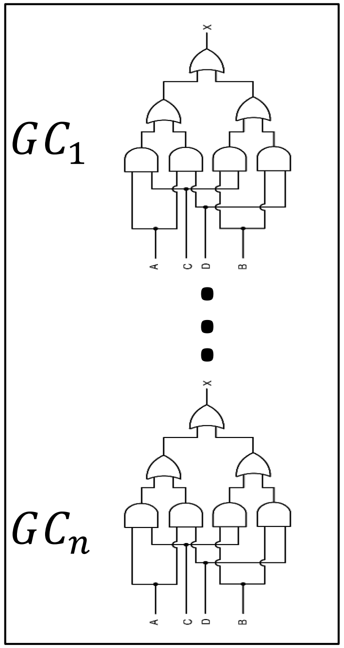
Eve should have keys to execute GCs on Alice's messages, but can't give her **ALL** keys

s_0, s_1

π_{OT}

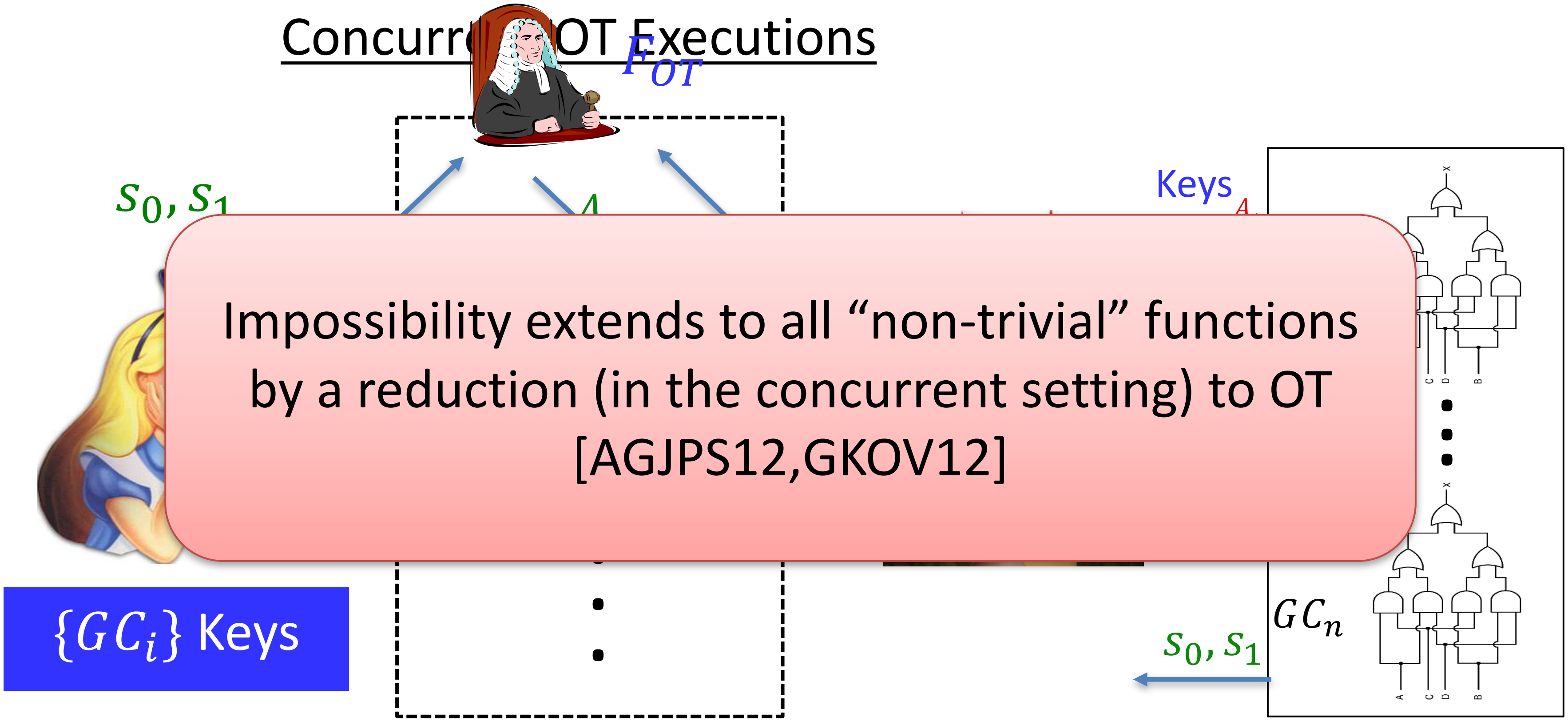


$\{GC_i\}$ Keys



Eve needs to run *extra* π_{OT} executions with Alice to get "necessary" keys

More Details



Impossibility extends to all "non-trivial" functions by a reduction (in the concurrent setting) to OT [AGJPS12,GKOV12]

Real World: Eve executes GCs one-by-one to learn s_0, s_1

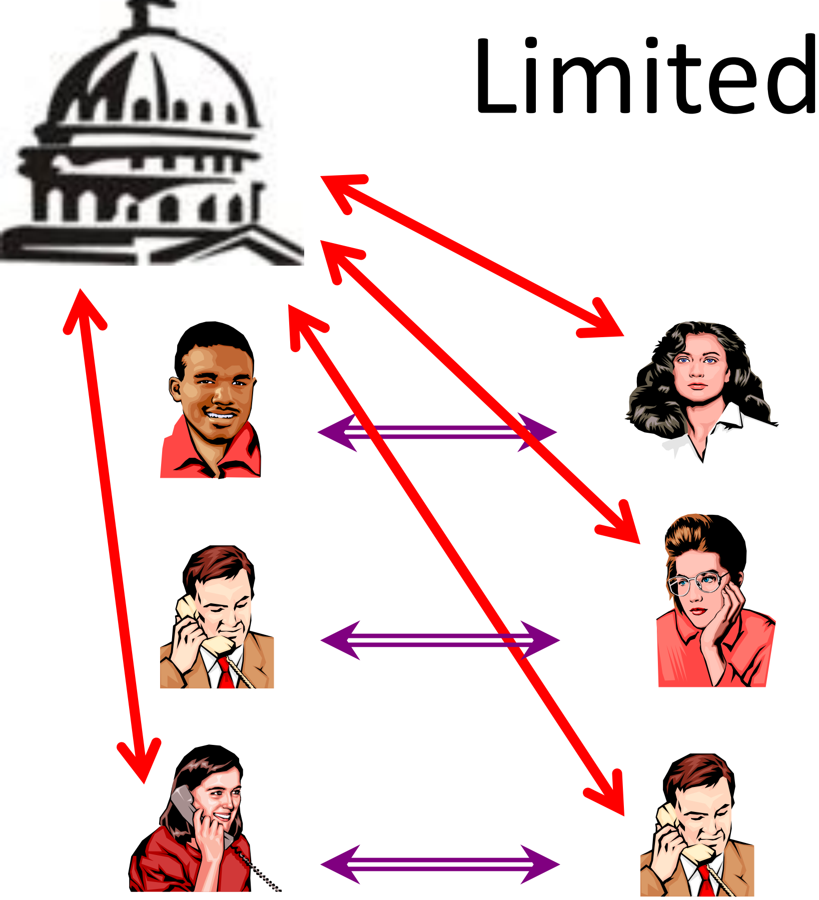
Ideal World: Attack fails as before due to security of GCs

What can we implement with Concurrent Security?

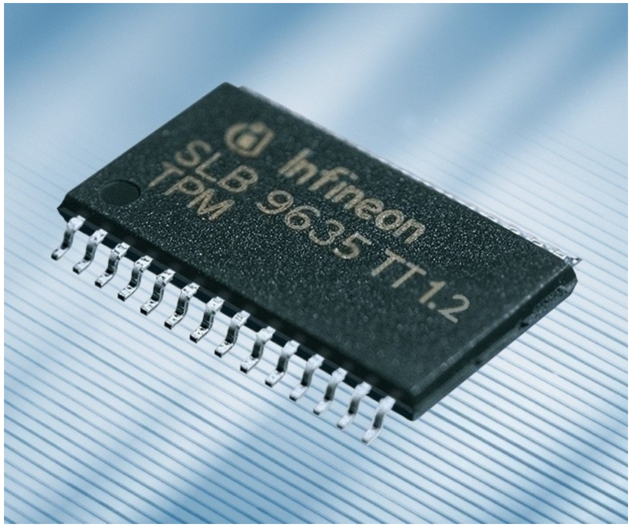
Theorem [CF, CKL, L]: It is impossible to achieve concurrent security for all "non-trivial functionalities"

SOLUTION: Get some "limited" **help** from a **trusted party**

Limited Trusted Help



Common Reference String (CRS)



Tamper Proof Hardware Model

VeriSign™
The Internet Trust Company℠

RSA
SECURITY™

Feasible in weaker models !

Honest Majority
[DM00,BGW88,BR89]

Tamper Proof Hardware
[K07,NW07,CGS08,MS08]

Common Reference String
[BFM88,D00,CLOS02,MGY03,
GO07,CPS07,DNO10]

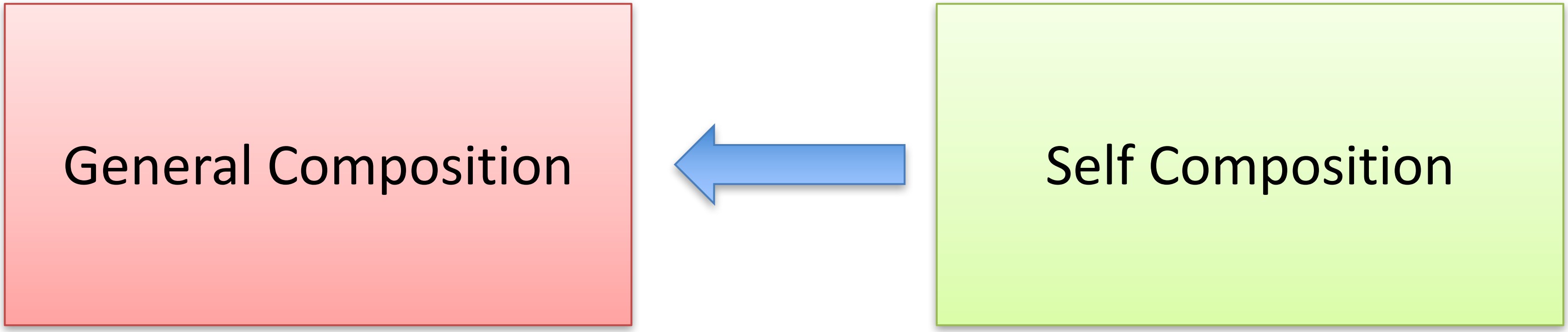
Timing
[DNS98,G06,LKP05]

Public-Key Infrastructure
[JSI96,DN03,BCNP04,DNO10]

Augmented CRS (GUC)
[CDPW07]

Concurrent Security
in a **Generalized UC** model

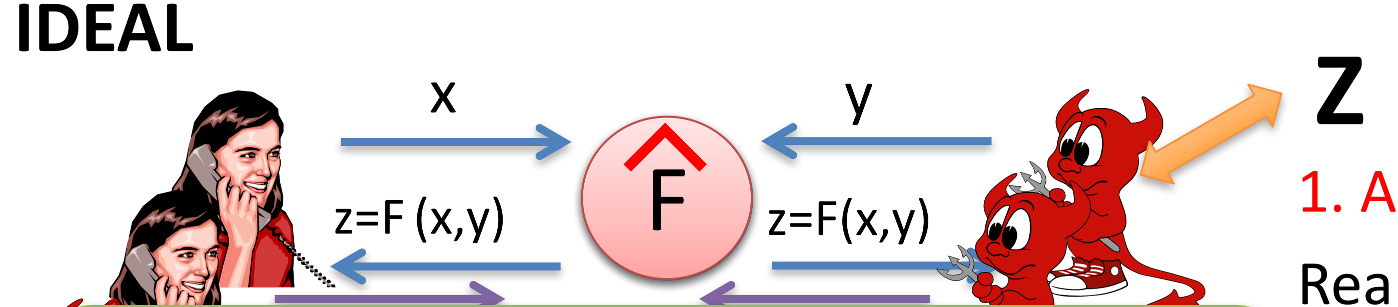
Intuition of Constructions



General Composition

Self Composition

Generalized UC [LPV09]



1. Augmented

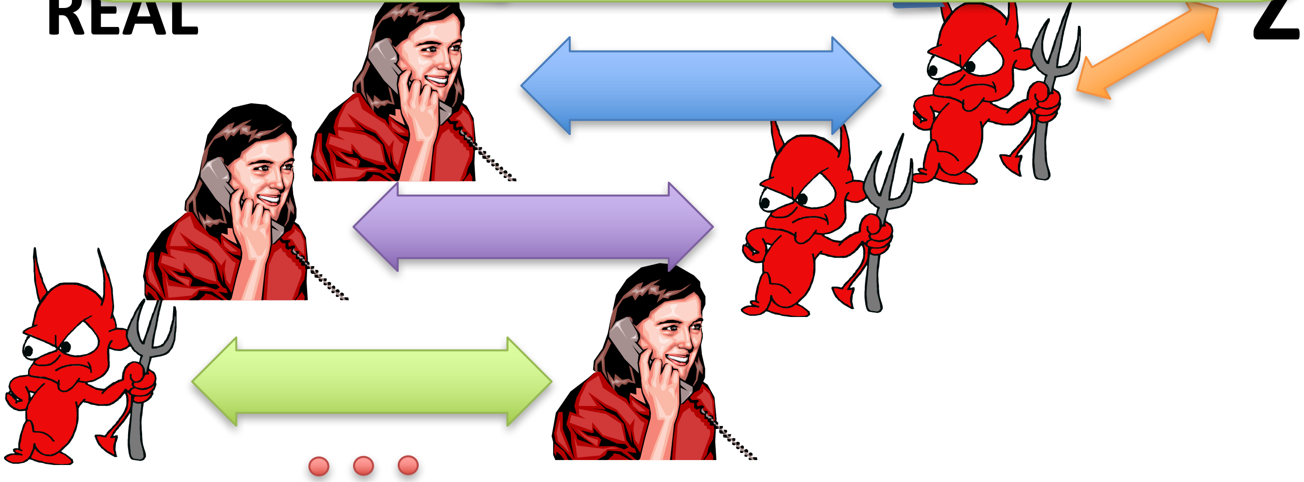
Real World

2. Multi-session

Ideal/Real World

A framework of models

- Embeds most weaker models
- Close to UC, leverage previous results



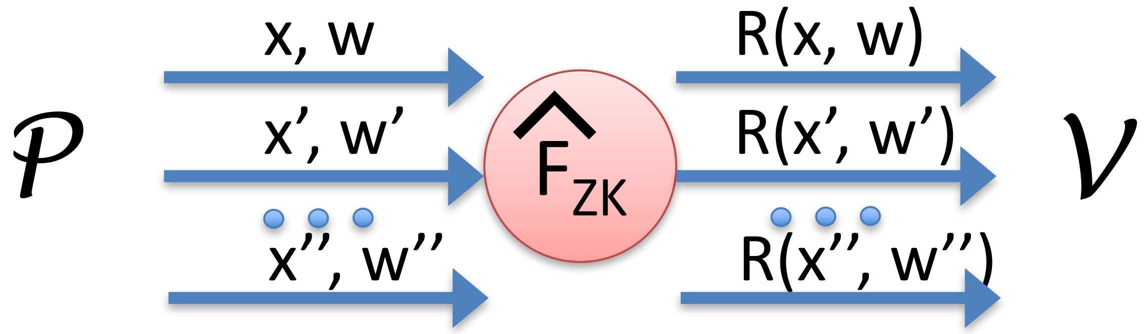
Concurrent MPC in Generalized UC

Compilation for UC

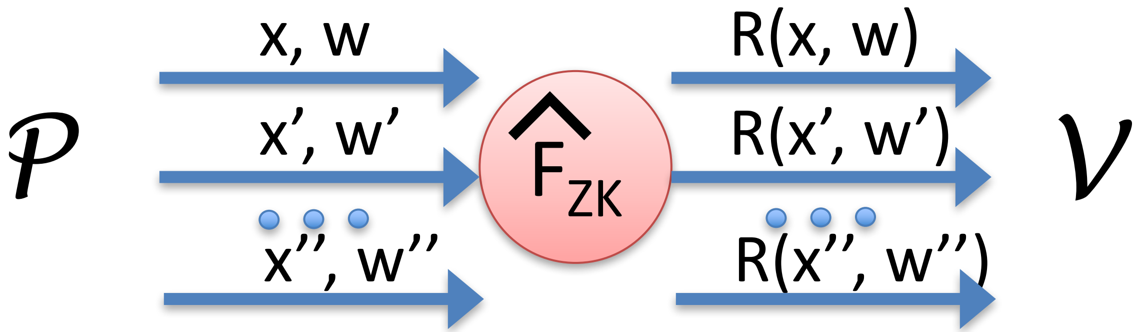
by [GMW87,BMR90,CLOS02,Pas04]

assuming Semi-Honest OT

Implement multi-session ZK functionality

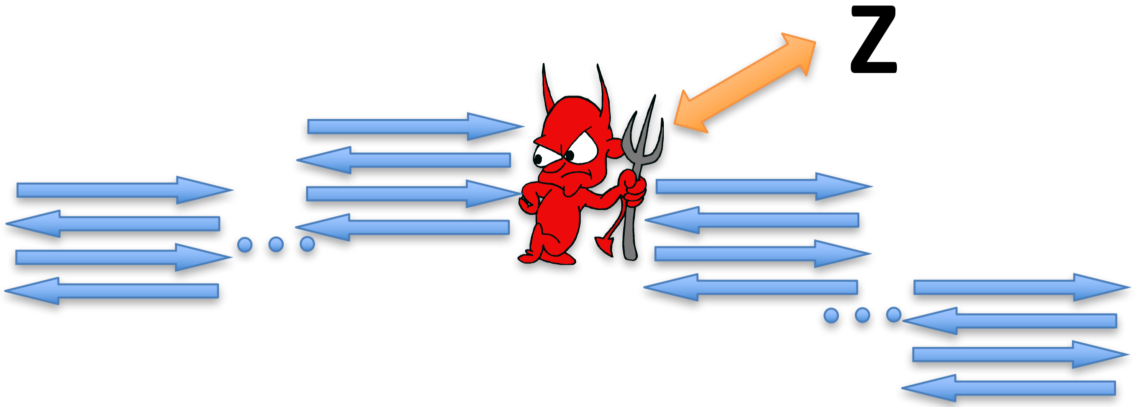


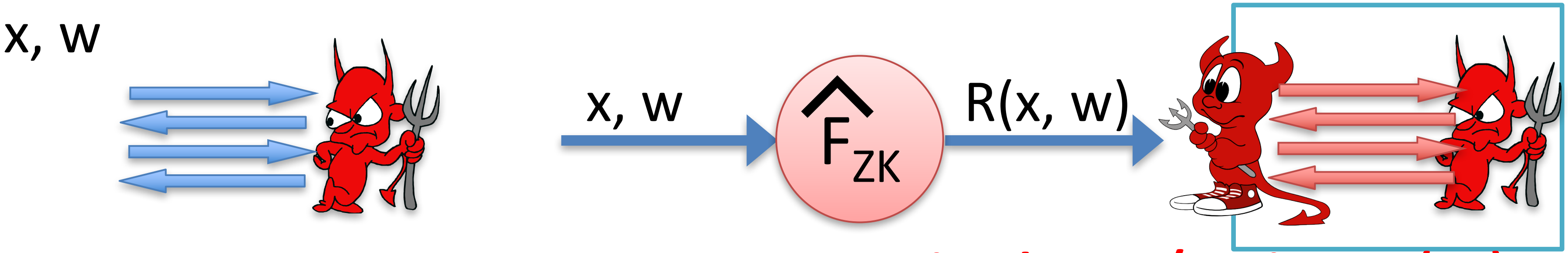
Implement multi-session ZK functionality



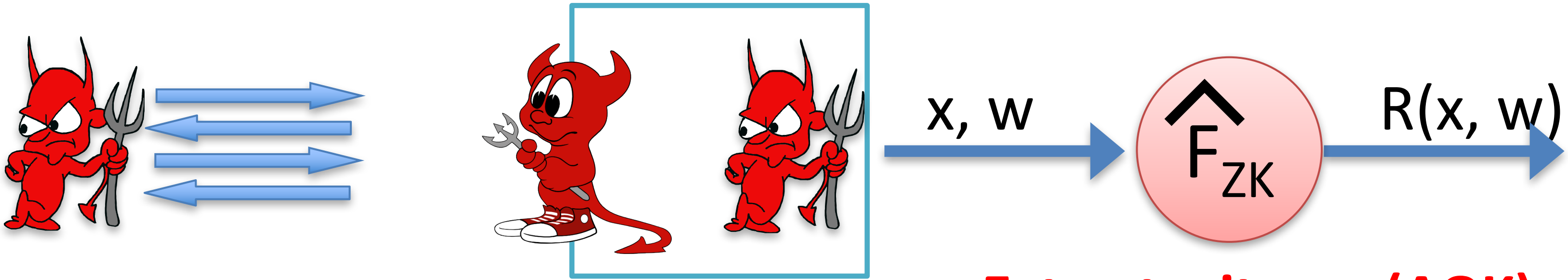
$$\approx$$

Design a “special” ZK protocol (P,V), s.t.

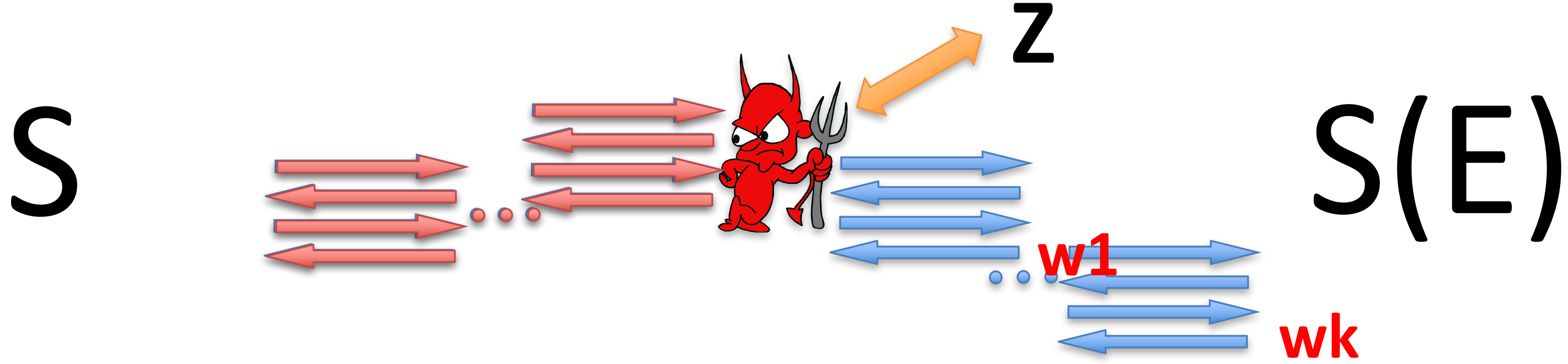




Simulate w/o witness (ZK)

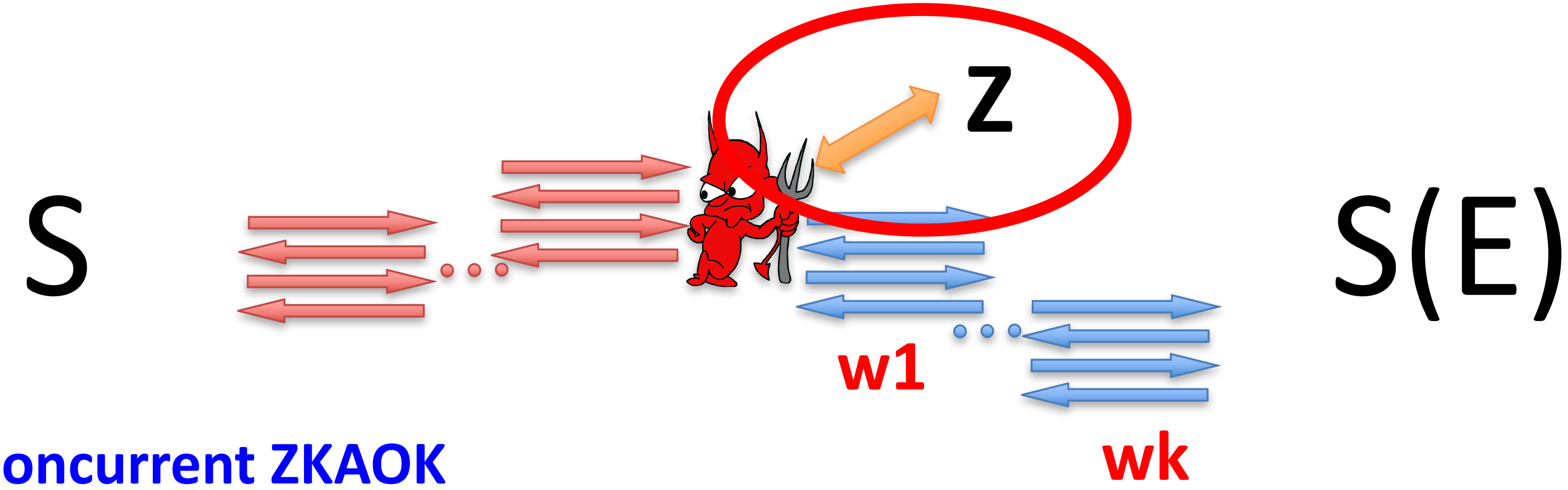


Extract witness (AOK)



Concurrent ZKAOK (Concurrent Simulation-Extractability)

Extract witnesses from adv even when receiving simulated proofs


S

Z

S(E)

w1

wk

Concurrent ZKAOK

Extract witnesses from adv even when receiving simulated proofs

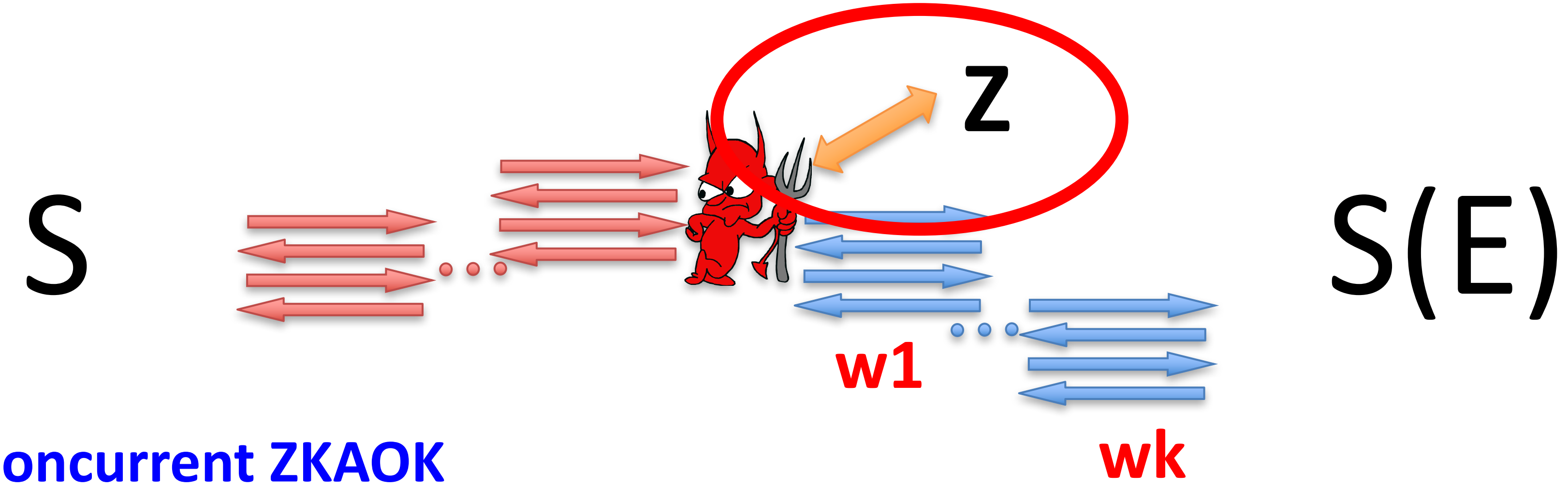
Have been studied a LOT !

in Concurrent ZK [DNS98,RK99,PRS02…]

All rewinding is strictly prohibited

Straight-line non-black-box simulation [Bar01…]

All Non-BB is strictly prohibited



Concurrent ZKAOK

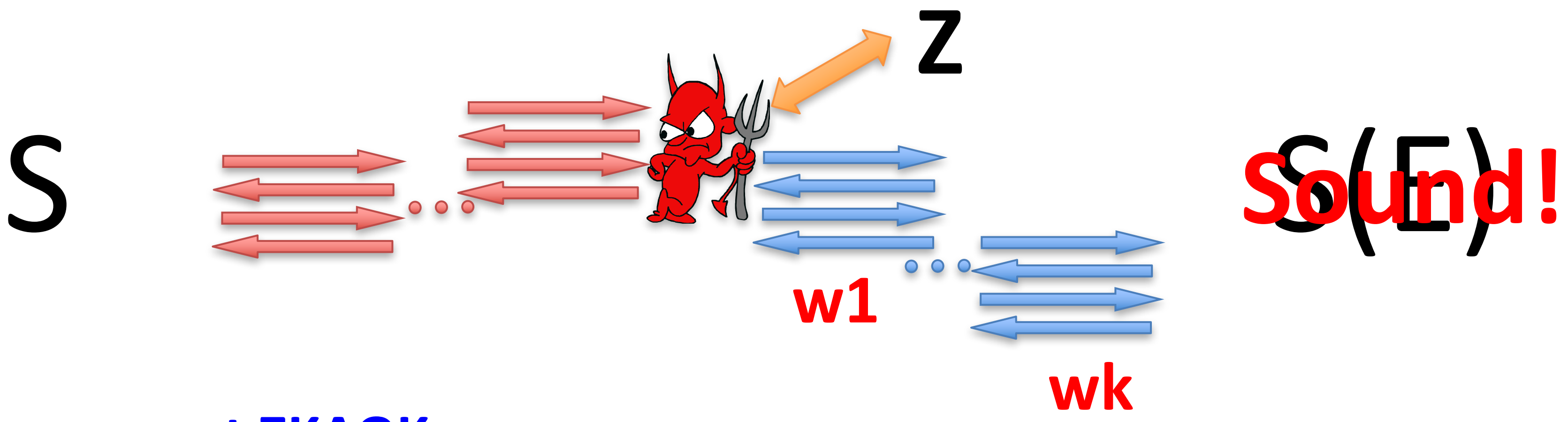
Extract witnesses from adv even when receiving simulated proofs

How to get straight-line simulation?

By giving **S** certain **SUPER-POWER** over **Adv**

= The ability to get a trapdoor

UC-puzzle + **Non-Malleability**

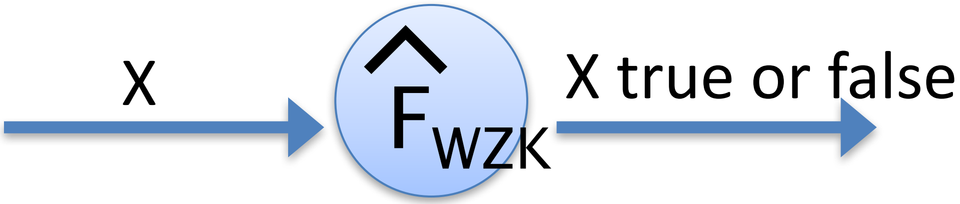


Concurrent ZKAOK

Extract witnesses from adv even when receiving simulated proofs

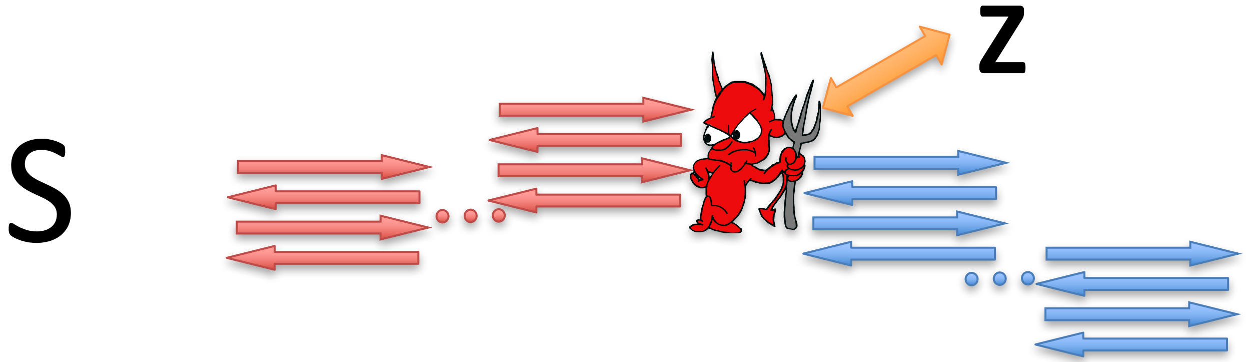
Compilation from ZKA to ZKAOK

[BL02,PR03,Pas04,DNO10,MPR10,LPV13]



A weaker notion: Fully concurrent ZKA (conc. simulation soundness)

Adv cannot cheat even when receiving simulated proofs

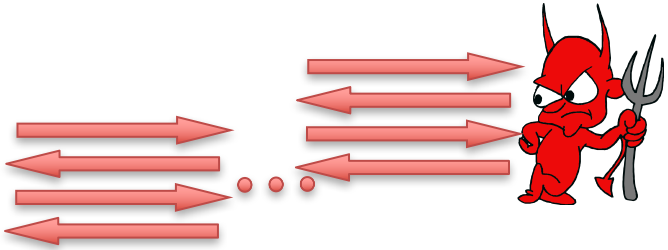


Sound!

A weaker notion: Fully concurrent ZKA

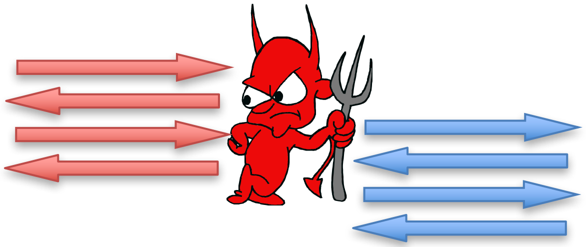
Adv cannot cheat even when receiving simulated proofs

Decompose



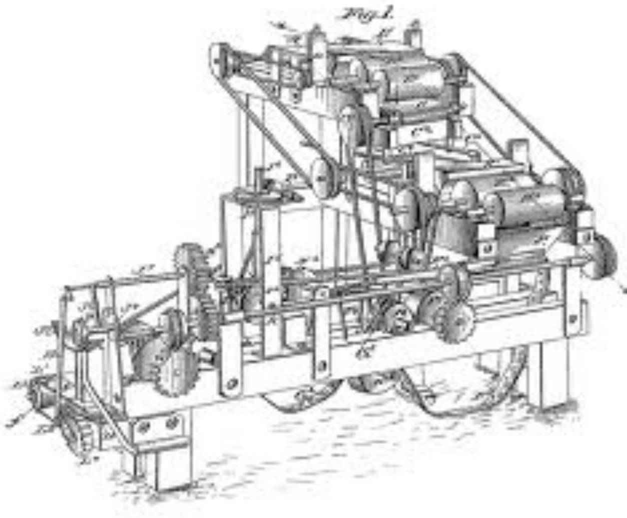
Concurrent Simulation

← UC-puzzles



Security against MIM attacks

← Non-Malleable Commitment



Concurrent MPC in Generalized UC

Unified Framework [LPV09,LPV12]

assuming SH-OT against C_{Sim}

UC-puzzle

NM Commitment

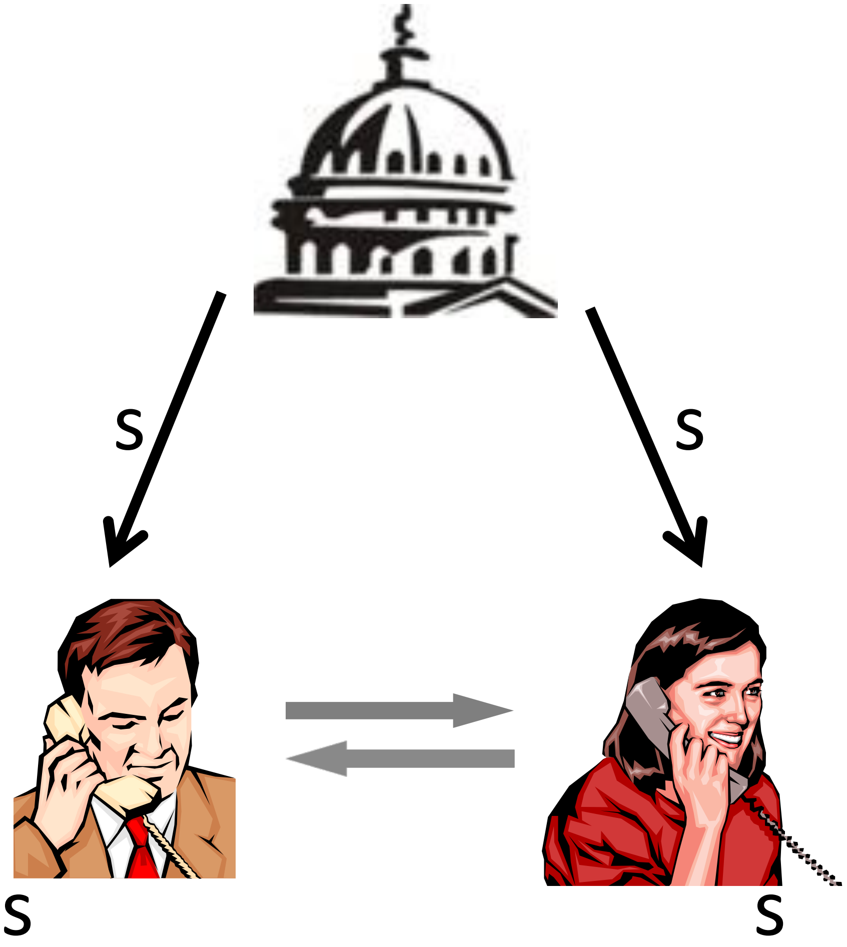
How to Cook Up Concurren rity

in Your Favorite Model X (CRS

1. *Instantiate a UC-puzzle using mode*
2. *Plug in*

Easy!

Common Reference String



Preprocessing:

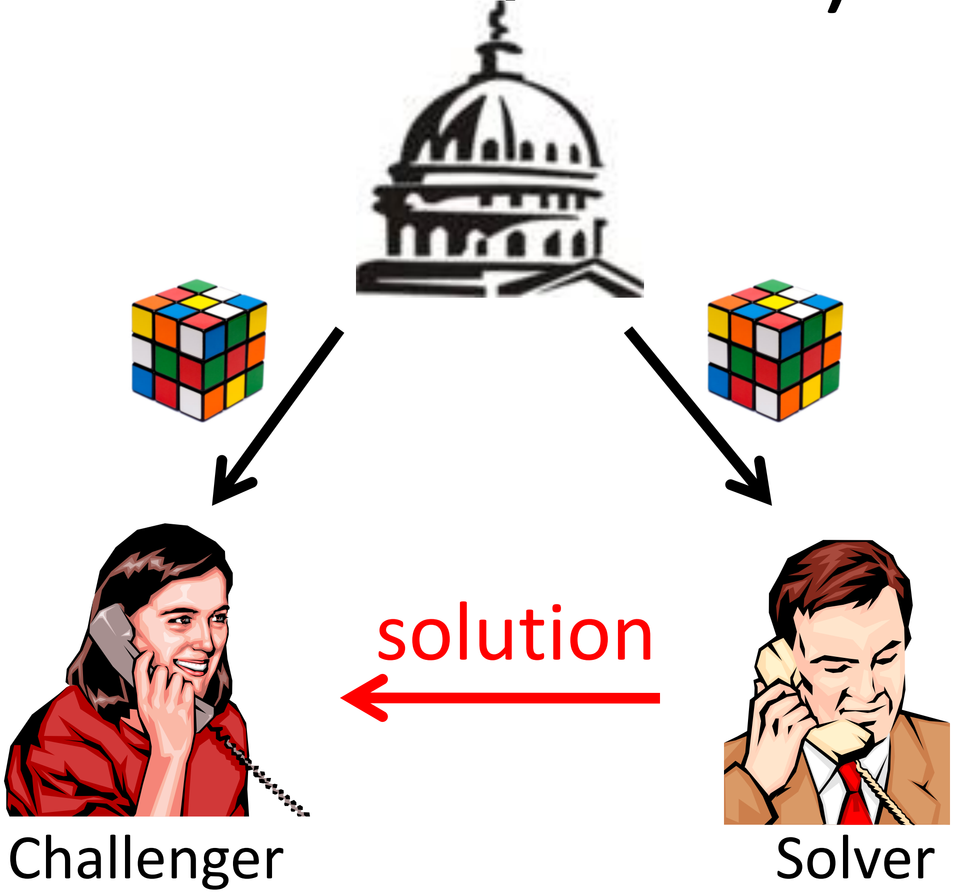
Trusted Party samples a distribution D and publishes it

Protocol Execution:

Parties exchange messages

THEOREM [CLOS02]: Every goal can be implemented with concurrent security in the CRS model.

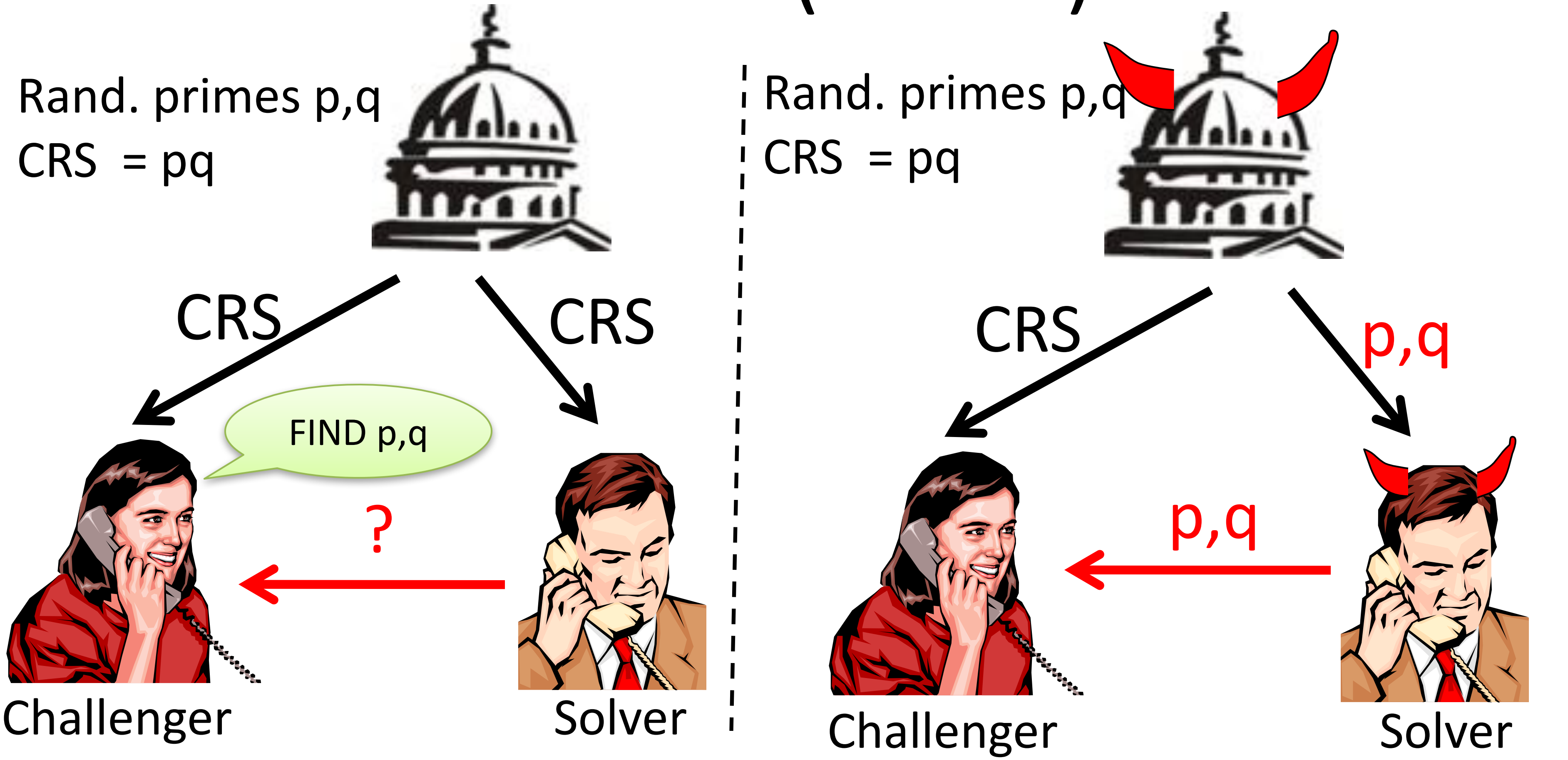
PUZZLE (in CRS)



Property 1: Hard to solve with trusted setup

Property 2: Easy to solve by controlling setup in an undetectable way

PUZZLE (in CRS)

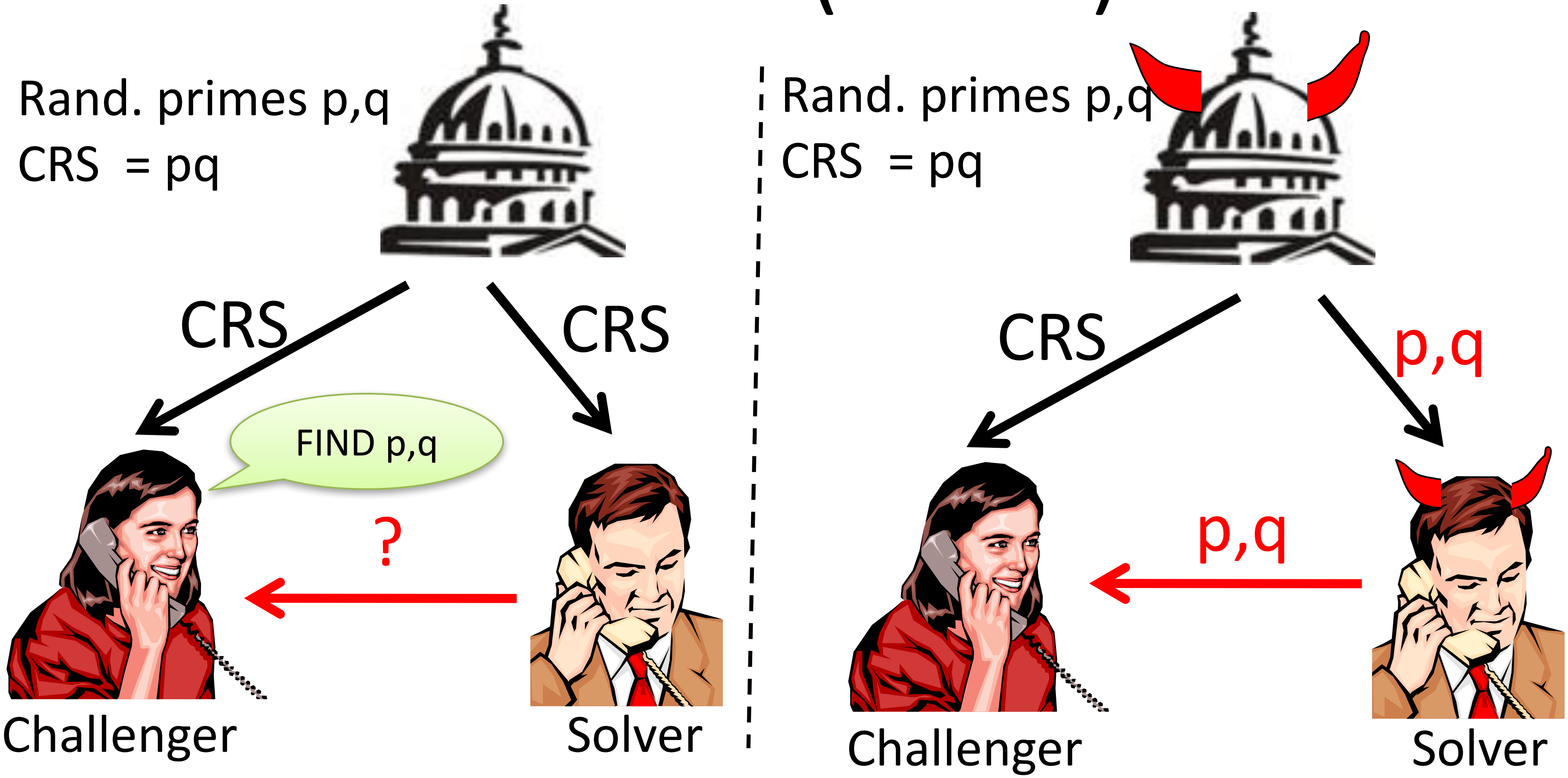


"Impossible assuming factoring is hard"

Property 1: Hard to solve with trusted setup

Property 2: Easy to solve by controlling setup in an undetectable way

PUZZLE (in CRS)



Rand. primes p,q
CRS = pq

Rand. primes p,q
CRS = pq

“Impossible assuming factoring is hard”

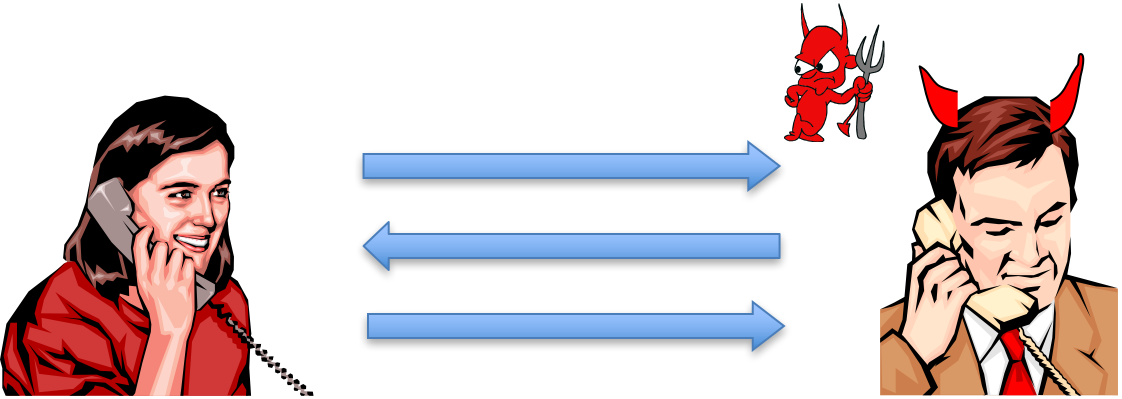
COROLLARY: Any goal can be implemented with concurrent security in the CRS model

The State of UC Security

- **Possible**: with limited "trusted help"
  - Trusted set-up models: Honest majority [BGW88, CCD88, BR89,DM00], CRS [BFM,CLOS], PKI [BCNP], Timing model [DNS,KLP], Tamper-proof Hardware [K], …

Thm [LPV09, LPV12] **For static corruption**,
UC-Puzzles provide a crisp and tight characterization for any setup

Are we done?



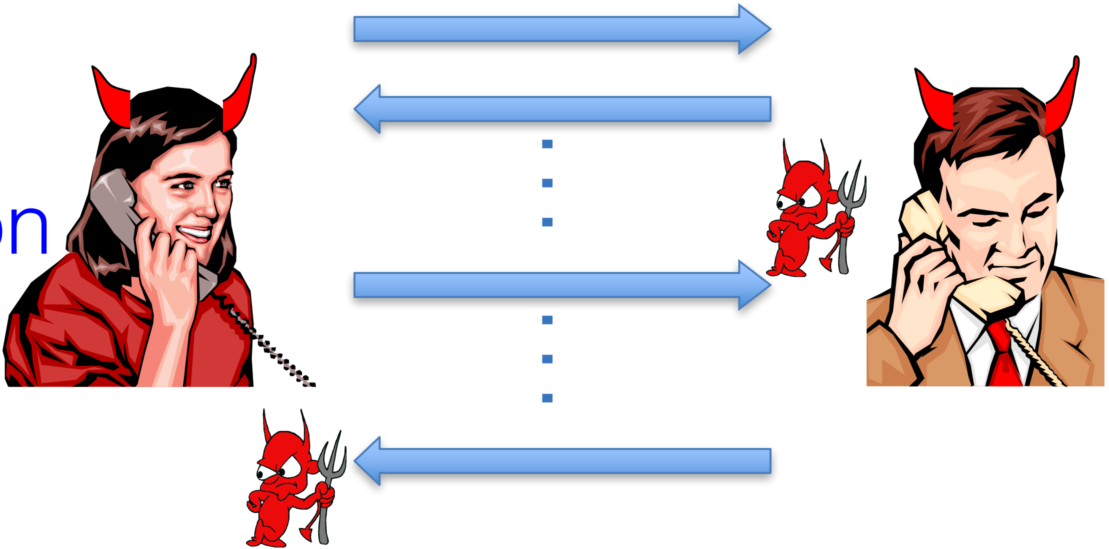
The Classic Static Corruption

corrupt in the beginning

But, Life is NOT STATIC

Adaptive Corruption

corrupt adaptively during execution



The State of UC Security

- **Possible**: with limited "trusted help"
  - Trusted set-up models: Honest majority [BGW88, CCD88, BR89,DM00], CRS [BFM,CLOS], PKI [BCNP], Timing model [DNS,KLP], Tamper-proof Hardware [K], …

Thm [LPV09, LPV12] **For static corruption**,
UC-Puzzles provide a crisp and tight characterization for any setup

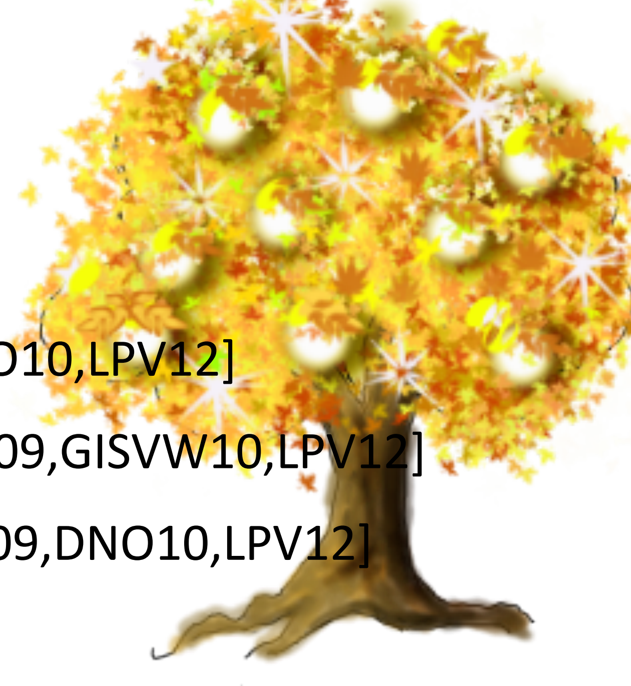
Thm [DMRV13, V14] **For adaptive corruption**,
(adaptive) UC-Puzzles are sufficient

Are we done, now?

All the approaches we have seen require some minimal trusted setup

But, in LIFE, Who Can You TRUST?

NO ONE!



In wonderland: **UC with TRUST**

- Honest Majority [DM00,BGW88,BR89]
- Public Key Registration [BCNP04,LPV09,DNO10,LPV12]
- Tamper-Proof Hardware [Kat07,CGS08,LPV09,GISVW10,LPV12]
- CRS [Can01,CLOS02,CPS07,CDPW07,GO07,LPV09,DNO10,LPV12]
- Timing Model [DNS98,KLP05,LPV09,LPV12]
- Physically Uncloneable Functions [BFSK11,OSVW13]

On earth: **relaxed security notions**

- Input Indistinguishable Computation [MPR06,GGJS12]
- Super-Polynomial-time Simulation [Pas03,BS05,LPV09,LPV12,GGJS12]
- Angel-based security [PS04,MMY06,CLP10,LP12,GLPPS13,KMO14]
- Multiple-ideal query security [GJO10,GJ13,GGJ13]

Ideal Goal:

- Fully composable / concurrent (i.e. UC)
- Tolerates adaptive corruptions
- No trusted setup
- Standard (polynomial-time) hardness
- Black-box in the underlying primitives

Super-Poly Time Simulation (SPS) [P'03]

We know, poly-time security reduction is impossible

Allow super-poly-time security reduction

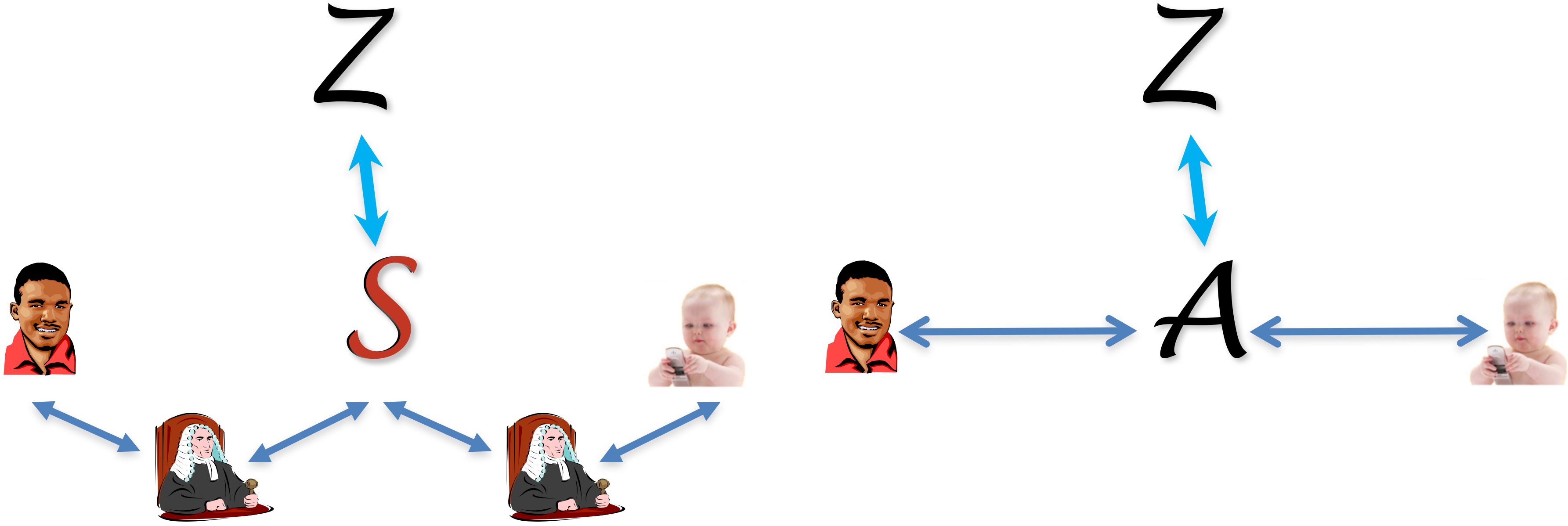
Possible!

Still, meaningful in many (most) cases

Static [P03,PS04,BS05,LPV09,GGJS12,LPV12]

Adaptive [BS05,DMRV13,V14]

But, using strong hardness assumptions



Angel-Based Security [PS04]

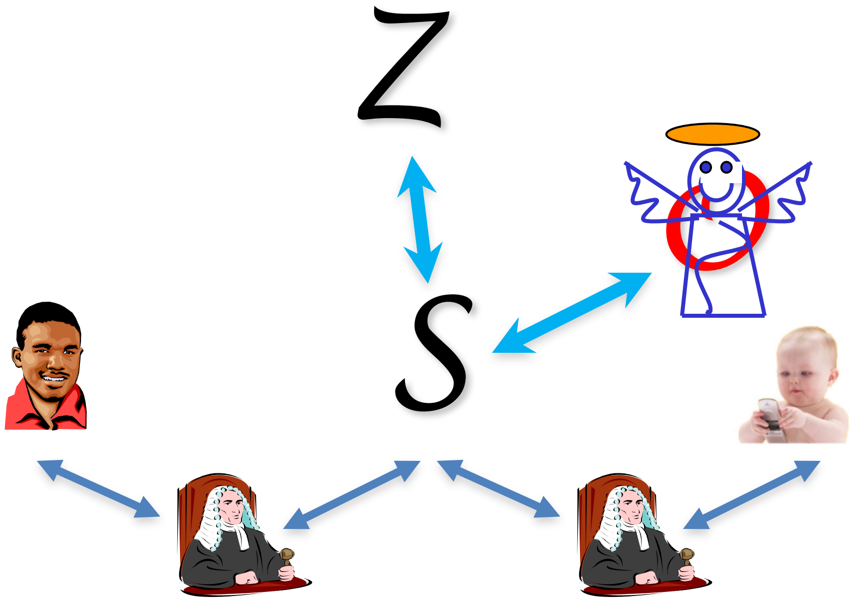
Simulator and Adv. receive help from an **angel**

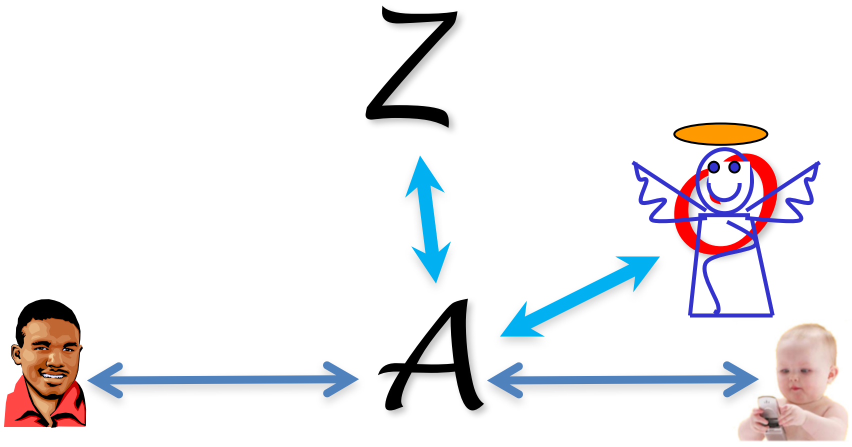
Angel: A restricted super-poly-time oracle

Possible w/ Static Composable [PS04,MMY06,BS05]**!**

But, even stronger assumptions

e.g. Adaptively hard CRH





Angel-Based Security [PS04]

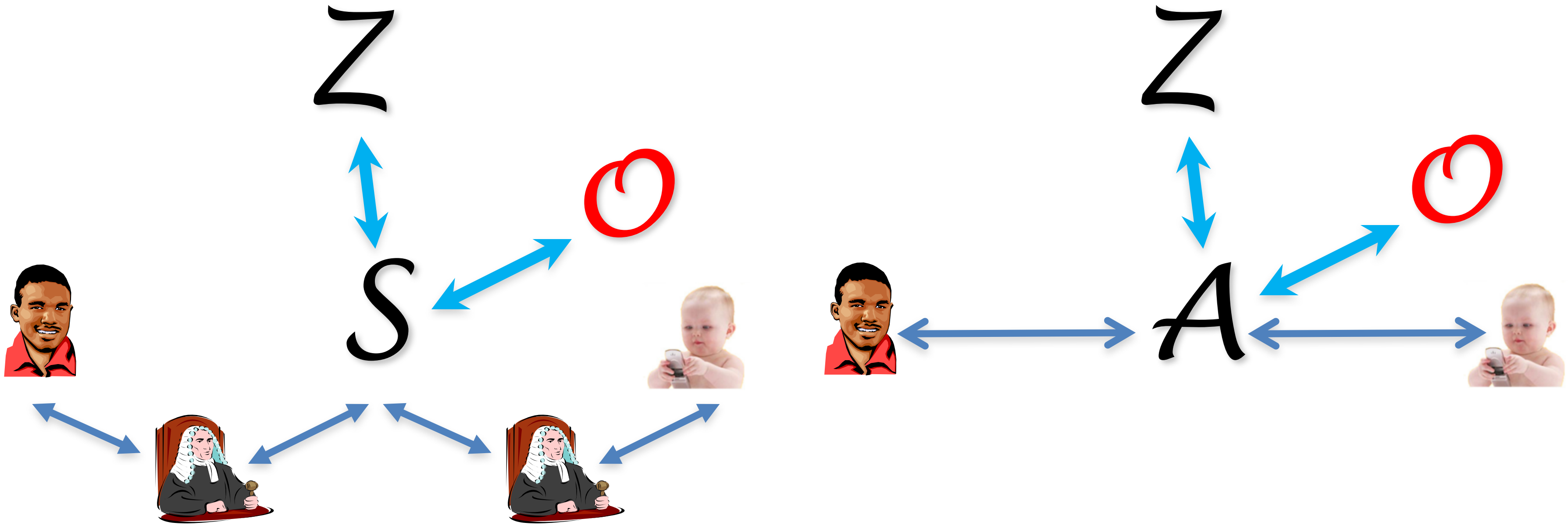
Simulator and Adv. receive help from an **angel**

Possible under polynomial-time assumptions!

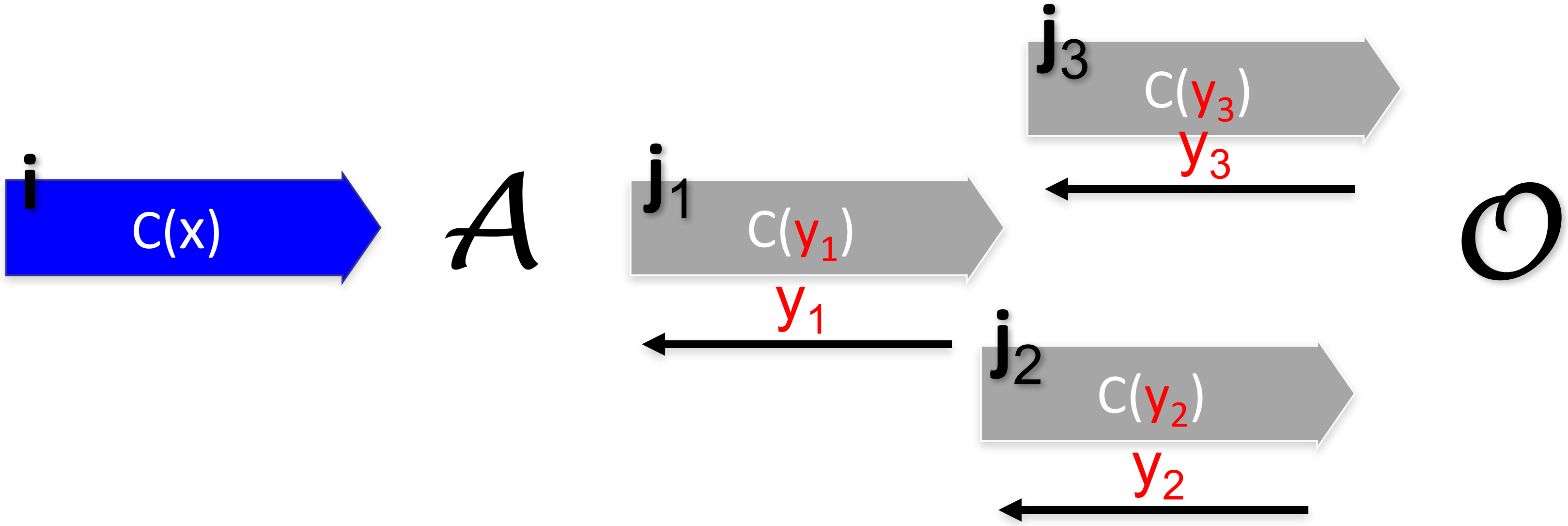
[CLP10]

Angel: Decommitment Oracle

New Primitive: CCA-secure Commitments



CCA-Secure Commitments [CLP10]

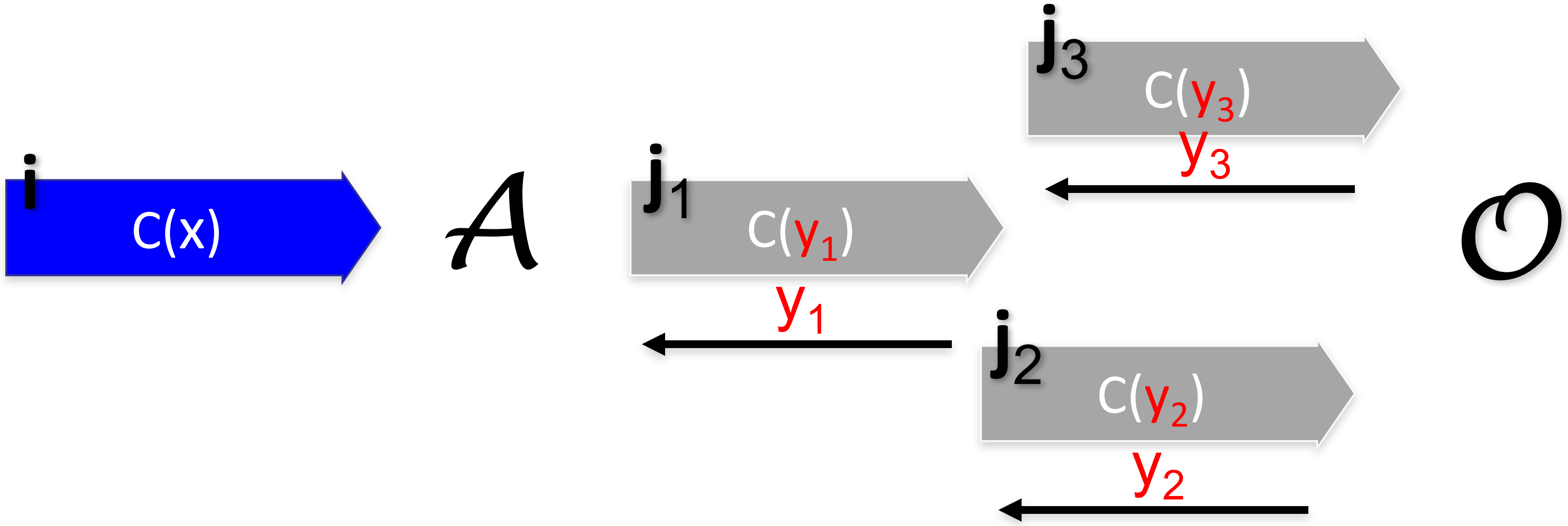


Chosen-Commitment-Attack (CCA) security:

Either $\mathcal{A}$ copies the left identifier to the right

Or LHS is hiding --- view of $\mathcal{A}$ indistinguishable

CCA-Secure Commitments [CLP10]



Chosen-Commitment-Attack (CCA) security:

Theorem [CLP10,LP11,GLPPS14,K14] Assuming **OWFs** ∃ $O(\log^2 n)$-round **Blackbox CCA Com.**

Theorem [CLP10,LP11] Assuming **CCA Com.** and **OT** ∃ BB construction **static (G)UC for any functionality**

Can we get Angel-Based Adaptive UC-Security?

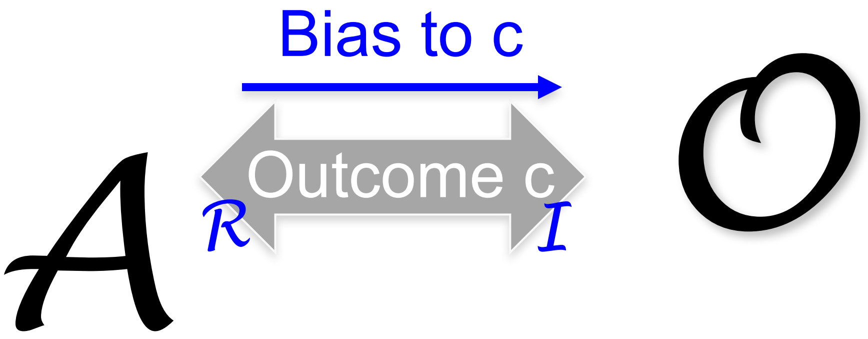
- Implies super-polynomial security, i.e. no setup
- Analyze single instance and guarantee composition (GUC [CDPW07])
- Possibility of polynomial-time assumptions by relying on rewinding based techniques

Bottleneck 1: [GS12] Rewinding based techniques don't compose well

Bottleneck 2: Adaptive Composable Commitments implies selective opening security IMPOSSIBLE! [ORSV11]

Our Approach: Adaptive CCA-Secure Coin-Tossing

Def 1: CCA-Secure Coin-Tossing $\langle I, R \rangle$



Chosen-Coin-Attack (CCA) security:

Angel: O is a biasing oracle

Security? Simulate a coin with A^O

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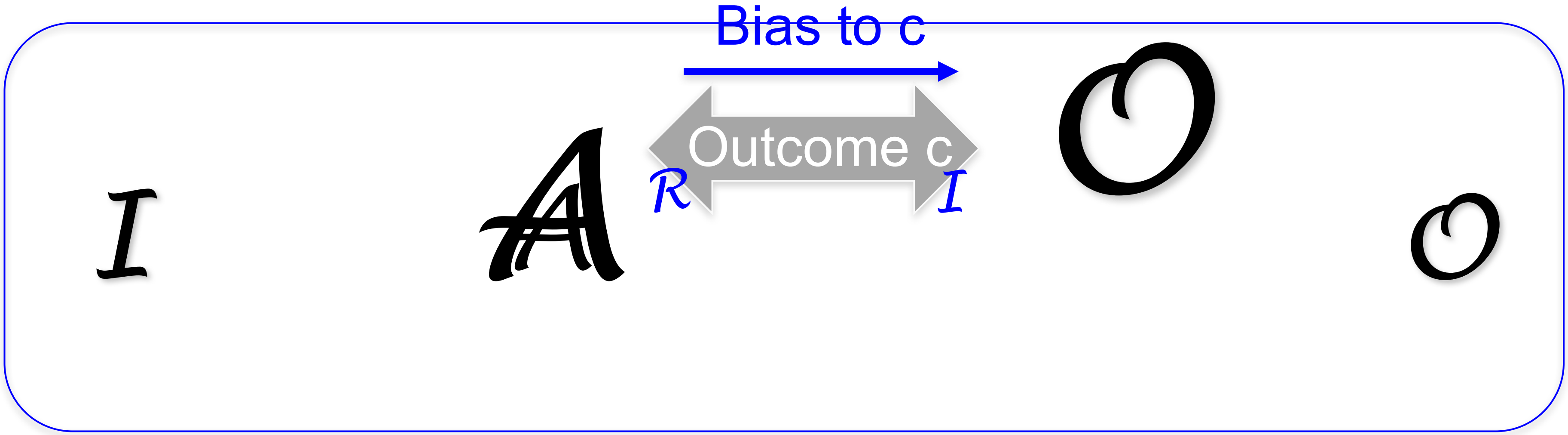

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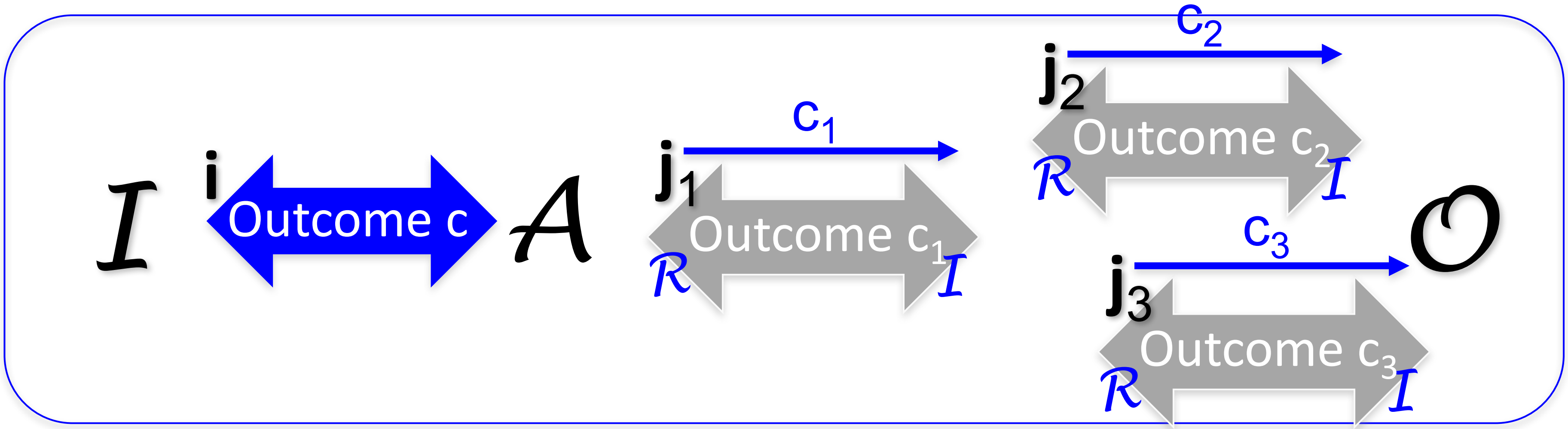

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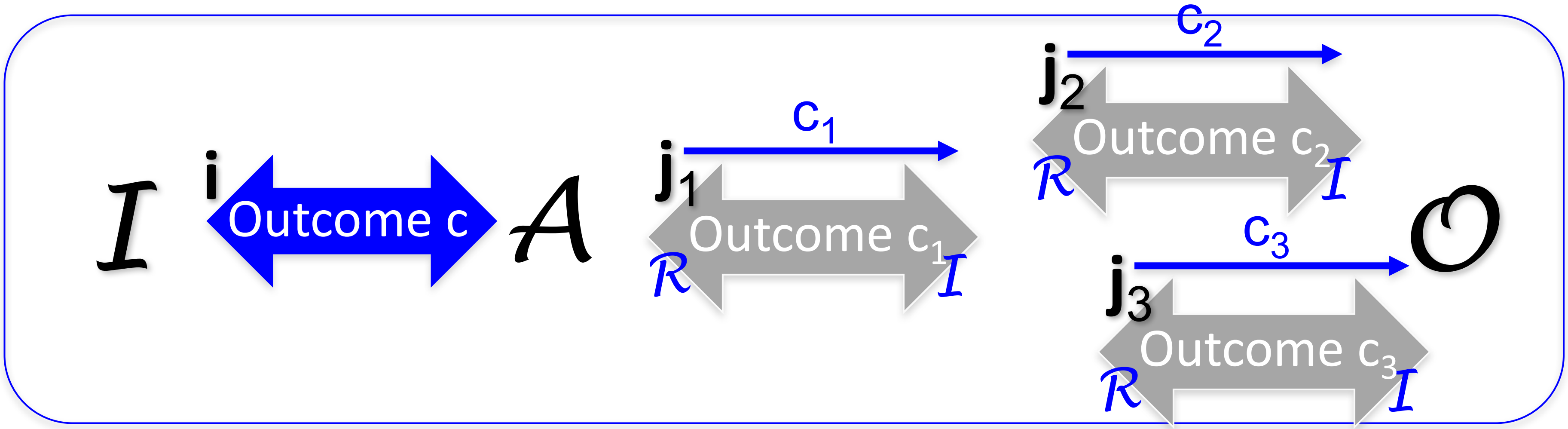

Chosen-Coin-Attack (CCA) security:

Either A copies the left identifier to the right or corrupts

Or LHS is **simulatable** --- view of A indistinguishable

Theorem 1: Assuming **CCA Coin-Tossing** and **sim. PKE**, adaptive UC-realize any (well-formed) functionality.

Theorem 2: Assuming **OWFs**, $O(n^{\varepsilon})$-round **CCA Coin-Tossing**

Adaptive UC Security without setup [HV16]

- ✓ **Polynomial-time assumptions (OWF+SimPKE)**
- ✓ **Fully black-box**

``Strongest” definition of concurrent adaptive security realizable without set-up

Open Problems

- General feasibility results are not practical
  - Many number of rounds
  - High communication complexity
  - Often non-black-box in the underlying cryptographic primitive
- [HV16] UC feasibility in the CRS under minimal assumptions in a black-box way (static & adap.)
- [HPV16,HPV17] UC feasibility in the Tamper Proof Hardware model (static & adap.)

Need: A unified “practical” way of getting UC

THANK YOU