On the composability, modularity, and security of cryptographic protocols

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Cryptographic protocols are basic building-blocks in fault-tolerant systems.

Examples:

- Secure communication:
  - Key exchange
  - Encryption (symmetric, asymmetric)
  - Digital signatures, authentication codes
- Agreement and broadcast:
  - Joint coin tossing
  - Secret sharing
  - Signatures

Cryptographic protocols are basic building-blocks in fault-tolerant systems.

More examples:

- Secure distributed depositories and services:
  - Threshold signatures, encryption
  - Secret sharing
- Secure and private information retrieval
- …

Analysis of cryptographic protocols is challenging:

- Security properties are not absolute:
  - Based on computational hardness assumptions (rather than being unconditional)
  - Involve probabilities of error
- Properties are complex to state, prove, and interpret.
- Properties are context-dependent (protocols may interact badly with each other)

Consequently:

Systems that involve cryptographic protocols are hard to analyze.

This holds even if the crypto is a ``small part'' of the overall system.

How to model and analyze such systems?

The formal methods approach: “abstract out” the crypto

- Analyze protocols in an abstract model where the crypto primitives are “ideal boxes”. E.g.:
  - Encryption provides absolute, tamper-proof secrecy and integrity [Dolev-Yao83]
  - Communication over a secure channel is completely unseen/untamperable by third parties [Abadi-Gordon93]
- “Hope” that the abstract protocols remain secure when realized using “real crypto”.

Advantages of the “formal methods approach”:

- Simplifies the analysis (no computational issues)
- Separates the “crypto part” from the “non-crypto” part

Disadvantages:

- Does not address potential flaws in, and bad interactions with, the “crypto part”
- Does not guarantee security of the “real protocol”

The traditional cryptographic approach:

- Adversary is a computational entity (resource-bounded Turing machine).
- Has access to the “real” bit-strings of communication.
- Security properties are formulated accordingly.

Advantage of the cryptographic approach:

– Guarantees security of “real protocols”

Disadvantages:

– Complex to state, prove, interpret…
– Cryptographic protocols do not “compose”
– Requires cryptographic modeling of the entire system, even if the crypto is only a small part.

General Goal

Would like to analyze fault-tolerant systems in a modular way:

- Represent the cryptographic parts as “ideal boxes”.
- Analyze the overall system assuming access to the “ideal crypto boxes”.
- Realize the “ideal crypto boxes” using real cryptographic protocols
- Deduce the security of the overall, “composed” system.

A framework for "universally composable security" [C01]

- Security of cryptographic protocols is defined via realizing an "idealized trusted service"
- A central property: protocols can be composed in a very general way while maintaining security.

Can be used to carry out the "modular analysis" approach.

Similar framework defined in [Pfitzmann-Waidner00,01]

Rest of the talk:

- Present the notion of security
- Present the composition theorem
- Discuss usage

The general definitional approach
[Goldreich-Micali-Wigderson87]

‘A protocol is secure for some task if it “emulates” an “ideal setting” where the parties hand their inputs to a “trusted party”, who locally computes the desired outputs and hands them back to the parties.’

Several formalizations of this fundamental approach exist **(e.g. [Goldwasser-Levin90,Micali-Rogaway91, Beaver91, Canetti93, Pfitzmann-Waidner94,Canetti00, Dodis-Micali00, Pfitzmann-Schunter-Waidner00]),** But:

- Only limited “secure composition” guarantees
- Typically restricted to “function evaluation”

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How security is defined (I):

1. Write an “ideal functionality” F that captures the requirements of the task at hand.

F is a “code for an ideal trusted service on the net”. (F Captures both correctness and secrecy requirements.)

Example:
The authenticated message transmission functionality

- Receive (A,B,m) from A
- Send (A,B,m) to B and the adversary, and halt.

Example: The *secure* message transmission functionality

- Receive (A,B,m) from A
- Send (A,B,m) to B, send (A,B,|m|) to the adversary, and halt.

Example:
The key-exchange functionality F_{KE}

- Upon receiving (“exchange”,A,B,sid) from parties A and B, do:
  - choose a random key *k.*
  - send *k* to A and B.
  - send (A,B,sid) to the adversary.
  - Halt.

(If either party asks to set the key to some value then F_{KE} agrees.)

Example:
The ZK functionality (for relation R)

- Receive (P,V,x,w) from P
- Receive (V,P,x) from V
- Send (R(x,w)) to V and halt.

Note:
- V is assured that it accepts only if R(x,w)=1 (soundness)
- P is assured that V learns nothing but R(x,w) (Zero-Knowledge)

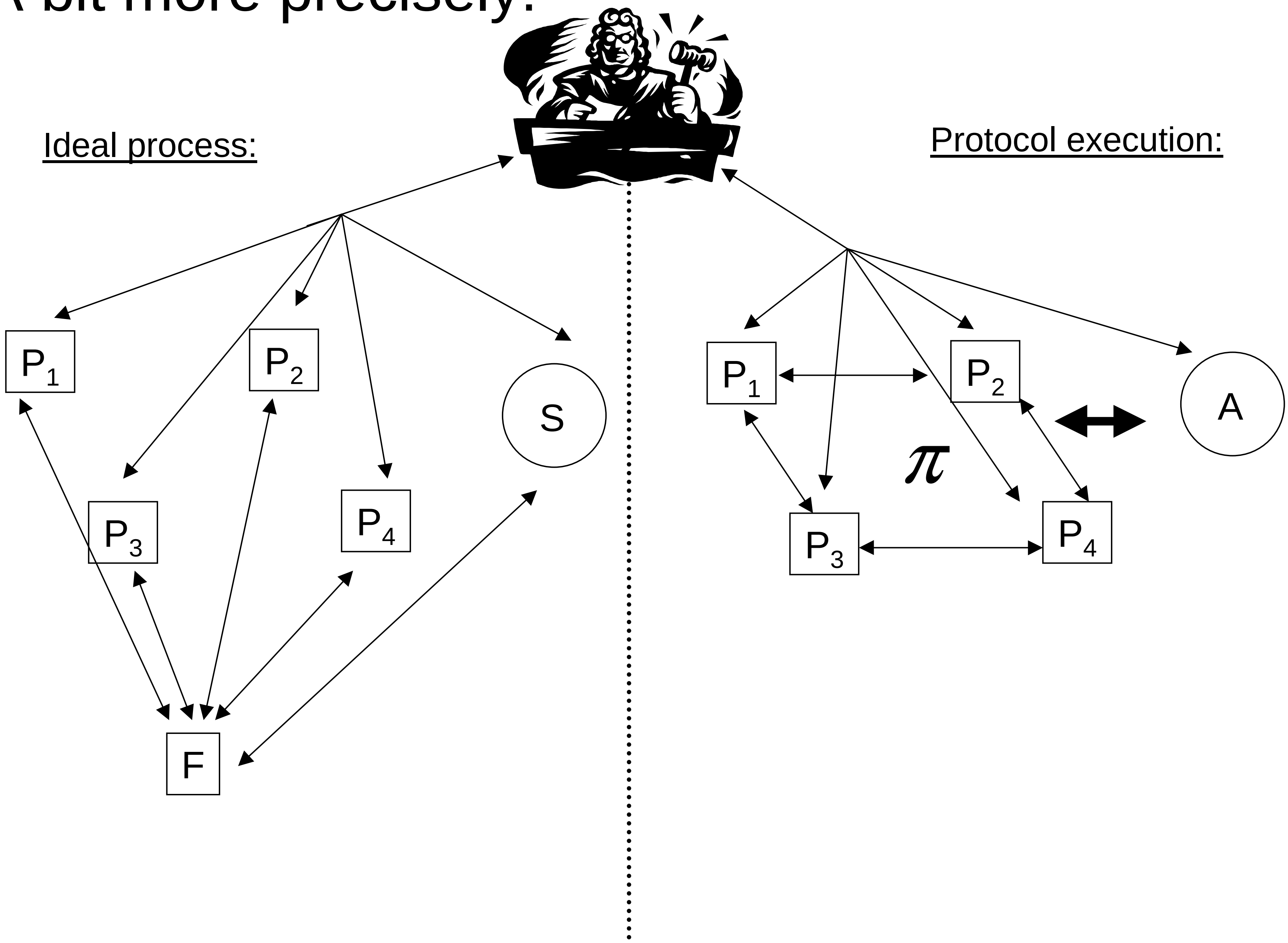
How security is defined (II):

2. Say that a protocol π *emulates* the ideal process for evaluating F if no "external environment" Z can tell between:

- A run of protocol π.
- An "ideal execution" where the parties interact with F.

(In this case, we say that π *securely realizes* functionality F.)

A bit more precisely:



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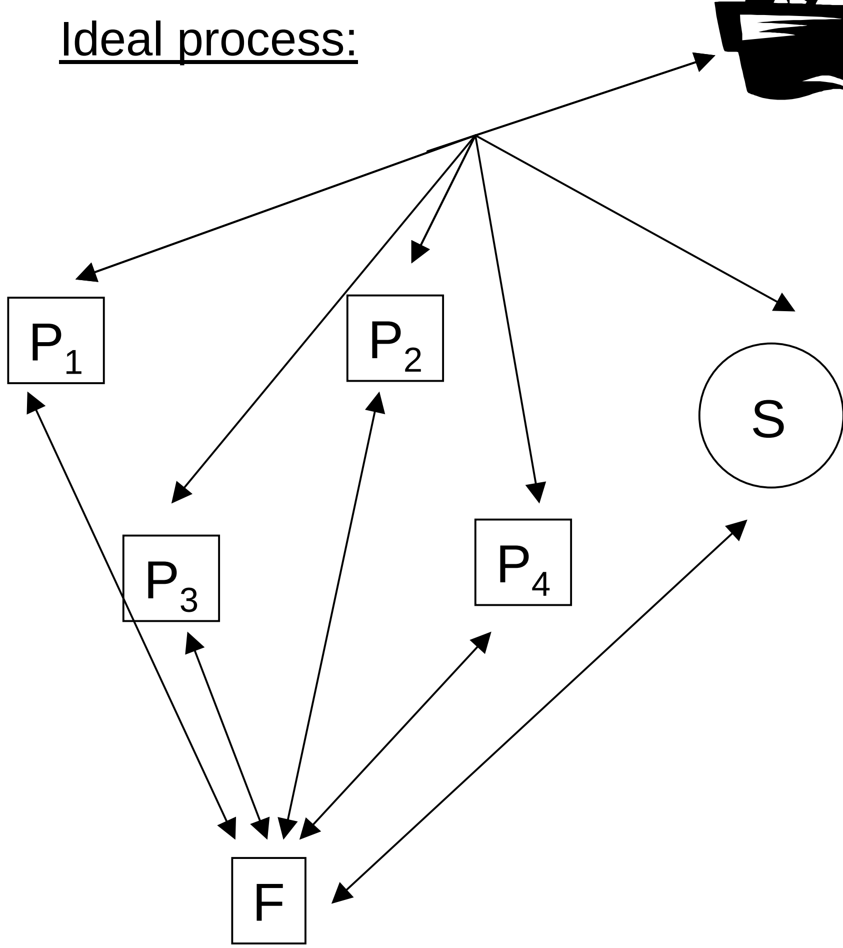
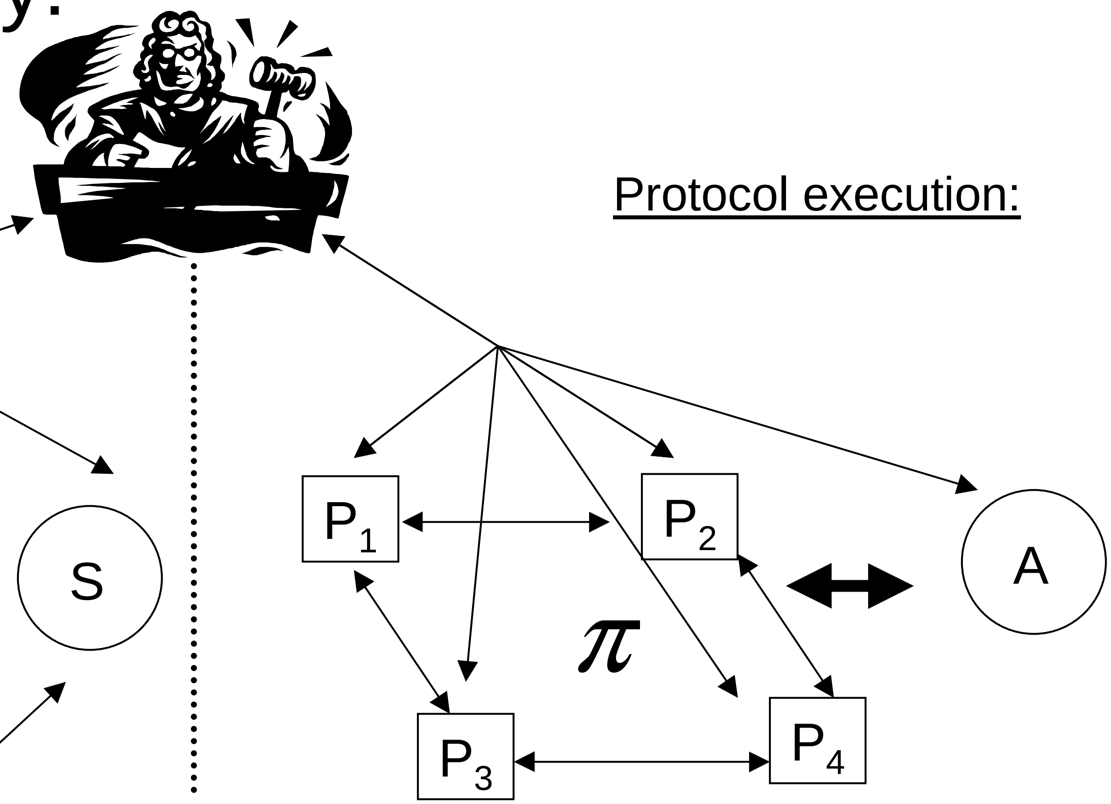




Protocol π securely realizes F if:

For any adversary A

There exists an adversary S

Such that no environment Z can tell whether it interacts with:

- A run of π with A
- An ideal run with F and S

Universal Composition:

1. Present the composition operation

2. State the composition theorem

The composition operation

(Originates with [Micali-Rogaway91])

Start with:

- Protocol ρ^F that uses ideal calls to F
- Protocol π that securely realizes F

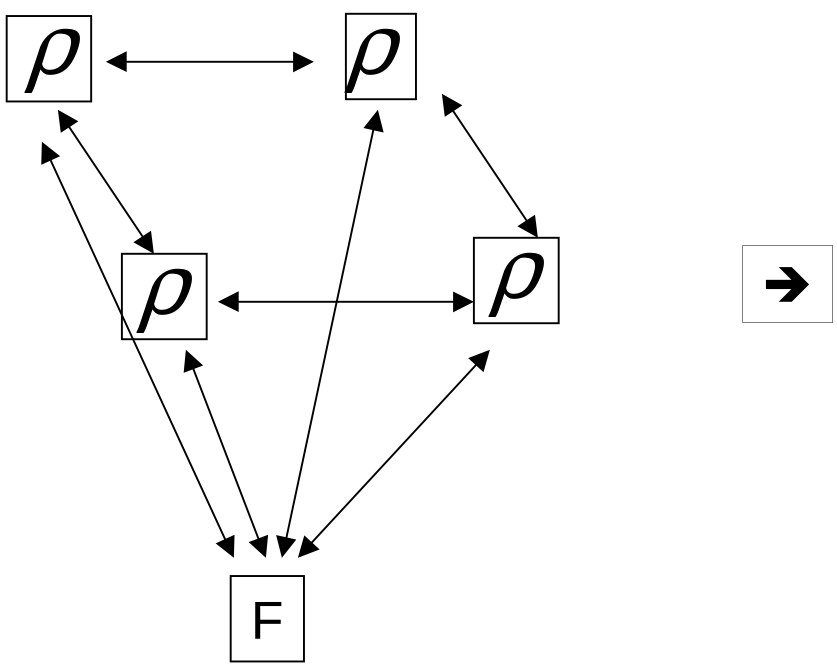
Construct the composed protocol ρ^π:

- Each call to F is replaced with an invocation of π.
- Each value returned from π is treated as coming from F.

Note: In ρ^F parties call many copies of F.

➔ In ρ^π many copies of π run concurrently.

The composition operation
(single call to F)



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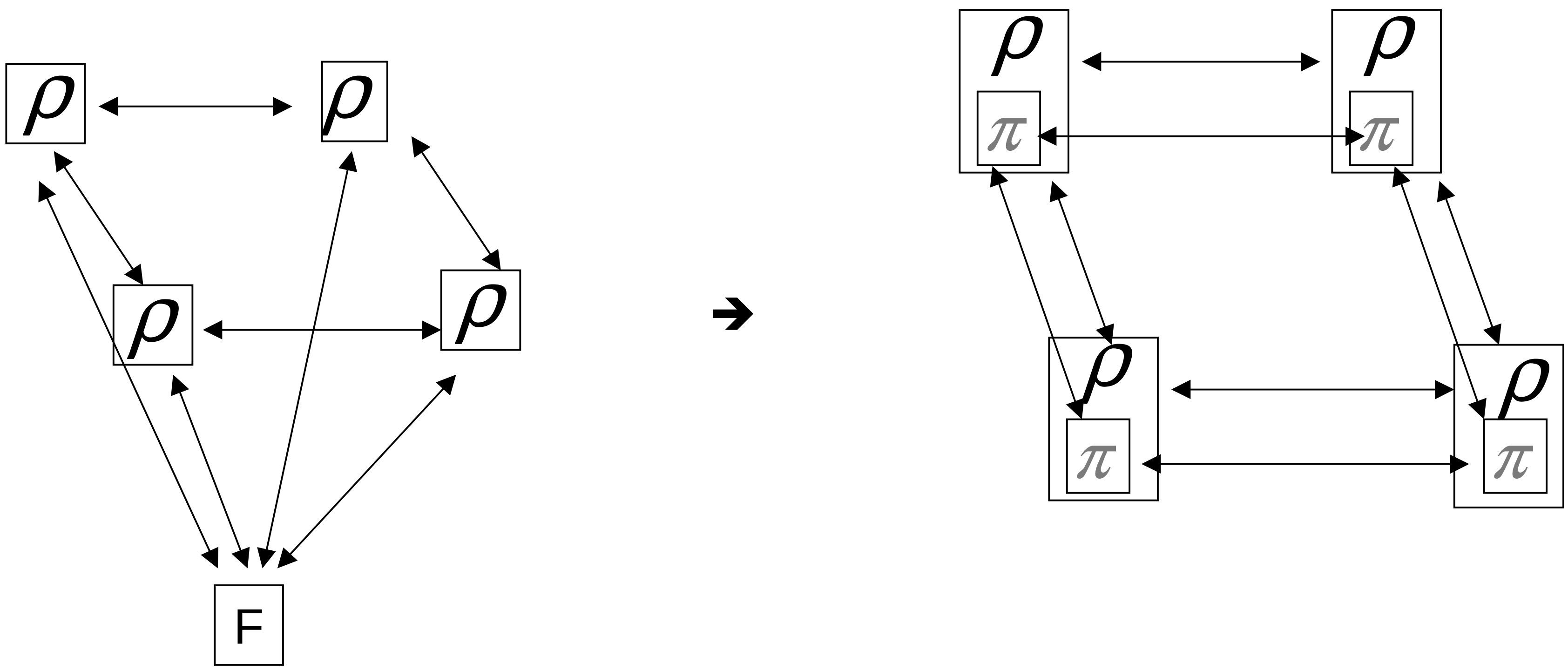

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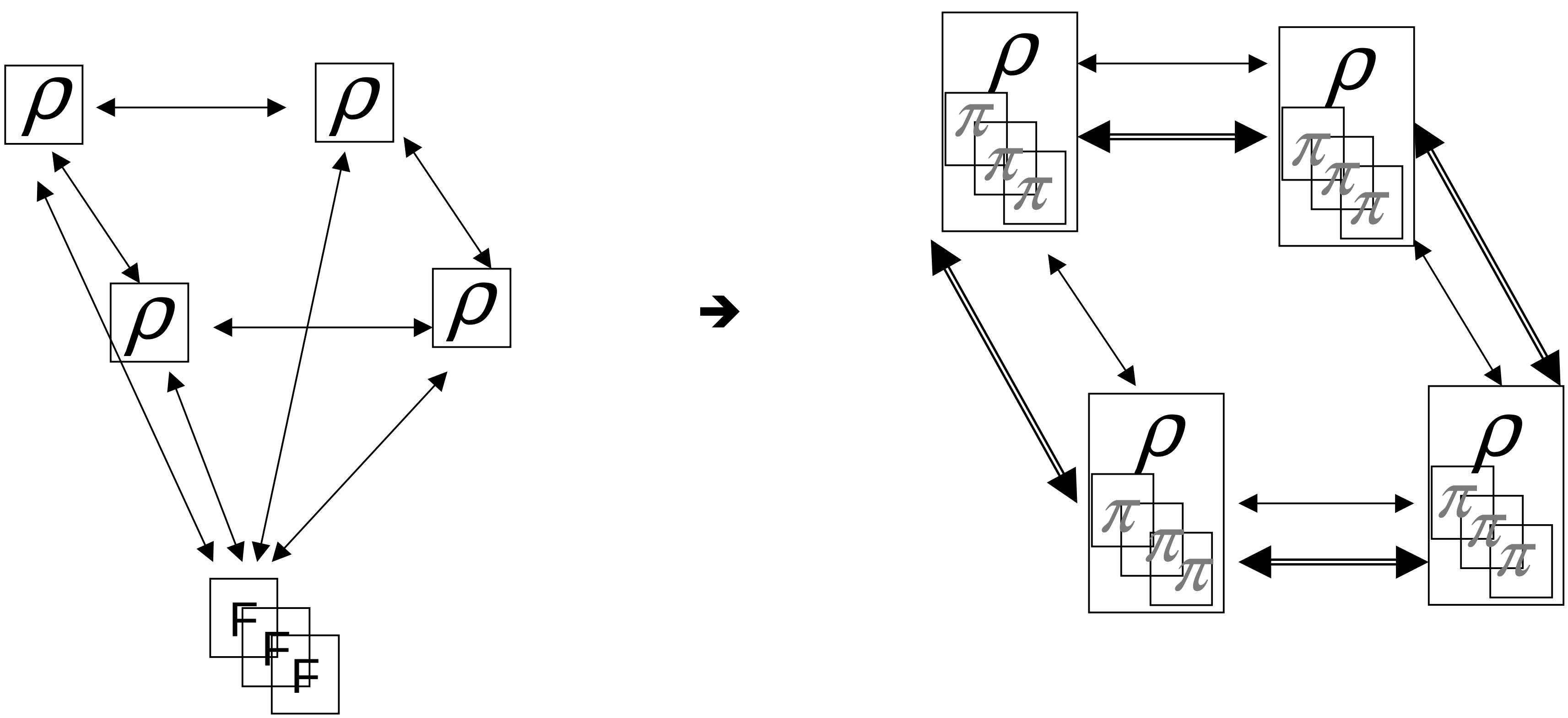

The universal composition theorem: [C. 01]

Protocol ρ^{π} "emulates" protocol ρ^{F}.

(That is, for any adversary A there exists an adversary A` such that no Z can tell whether it is interacting with ($\rho^{\pi}$, A) or with ($\rho^{F}$,A`).)

Corollary: If ρ^{F} securely realizes functionality G then so does ρ^{π}

(Weaker composition theorems were proven in e.g. [Micali-Rogaway91, Canetti00, Dodis-Micali00, Pfitzmann-Schunter-Waidner00].)

Implications of the UC theorem

- Can design and analyze protocols in a modular way:
  - Partition a given task T to simpler sub-tasks $T_1 \ldots T_k$
  - Construct protocols for realizing $T_1 \ldots T_k$.
  - Construct a protocol for T assuming ideal access to $T_1 \ldots T_k$.
  - Use the composition theorem to obtain a protocol for T from scratch.

(Analogous to subroutine composition for correctness of programs, but with an added security guarantee.)

Implications of the UC theorem

- Assume protocol π securely realizes ideal functionality F. Can deduce security of π in any multi-execution environment:

As far as the environment is concerned, interacting with (multiple copies of) π *is equivalent to interacting with (multiple copies of) F.*

Formulating “ideal crypto boxes” within the UC framework

- Write ideal functionalities that capture security properties of known primitives
- Show that the functionalities can be realized via cryptographic protocols
- Can now analyze protocols assuming access to the ideal functionalities.
  (this is often doable without getting into computational issues)

Was done for:

- Digital signatures
- Public-key encryption
- Key exchange
- Secure communication
- Two-party protocols (commitment, ZK, oblivious transfer, coin tossing,…)
- General multi-party functionalities

(Work done in C01, Pfitzmann-Waidner01, C-Fischlin01, C-Lindell-Ostrovsky-Sahai01, C-Krawczyk02, Backes-Pfitzmann-Waidner03,…)

Two approaches for writing functionalities

- Approach 1: Have multiple copies of simple ideal functionalities [C01].
  - Define separate functionalities for encryption, signature, authentication, key exchange, etc.
  - Each functionality for a single instance.
- Approach 2: Have a single “monolithic” ideal functionality that represents all the crypto [BPW03].
  - A single functionality captures all instances of all crypto primitives used in the system.

Future work

- Write ideal functionalities for representing more cryptographic primitives.
- Prove security of more protocols in the UC framework
- Design formal tools for analyzing security of protocols within the UC framework, assuming ideal access to crypto primitives.

End goal: Automated, cryptographically sound analysis.

General goal:

Would like to combine the two analytical apporaches, to get “the best of both worlds”.

(First attempts done by [Abadi-Rogaway01,…])