Contract-Signing Protocols

J. Mitchell

Before contract signing …

- Questions about projects? Want help?
  - Contact Arnab this week for suggestions
- Discussion of security properties
  - Authentication
  - Secrecy
- Precise definitions
  - Set of runs of a system
  - When a run violates a security condition
    - Definition of *successful attack*
  - Safety vs liveness properties

Protocol

- A Protocol is defined by a set of roles, and initial conditions (if needed)
- What is a role?
  - A "program" executed at one site
  - Includes communication, internal actions
- What are initial conditions?
  - Example: each agent has a secret key, shared only with the server
  - Example: each agent knows the public verification key for every other agent's digital signature key

Example roles: NSL protocol

```
new m;
send encrypt( Key(Y), ⟨X,m⟩ );
recv encrypt( Key(X), ⟨m, Y, n⟩ );
send encrypt( Key(Y), n )
```

"Alice"

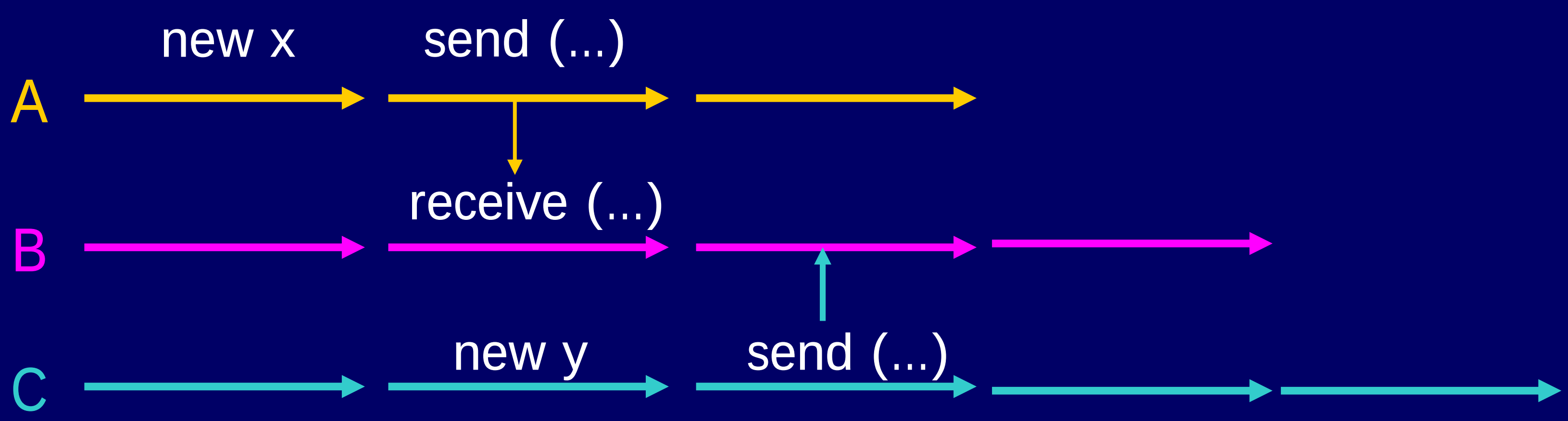
```
recv encrypt( Key(Y), ⟨X,m⟩ );
new n;
send encrypt( Key(X), ⟨m, Y, n⟩ );
recv encrypt( Key(Y), n )
```

"Bob"

Initial conditions: each agent has a private key and knows the public keys of other agents

Execution model

- Initial configuration
  - Set of principals and keys
  - Assignment of ≥1 role to each principal
- Run



Honest principals follow roles of the protocol; some agents may be dishonest

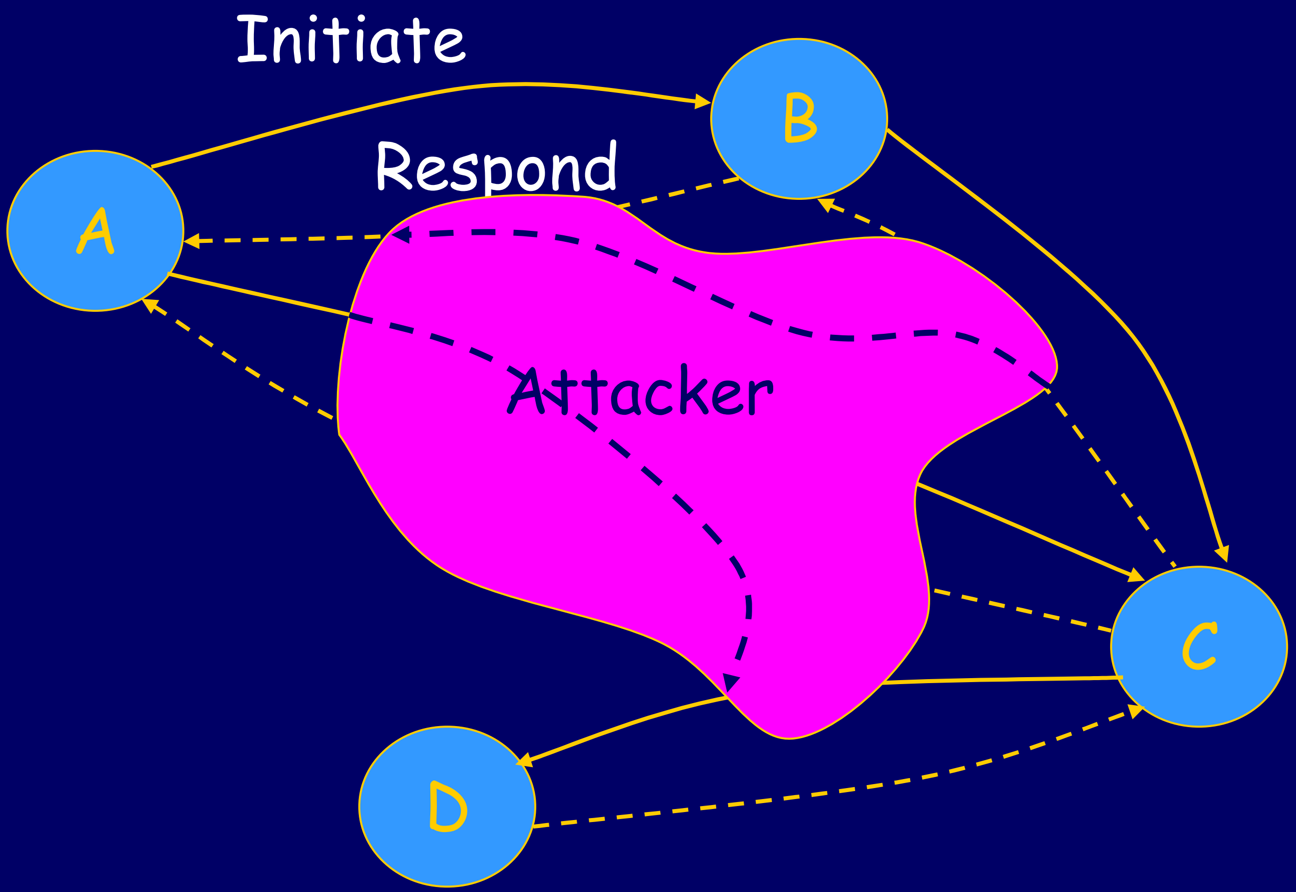
Actions can be arranged in a linear trace

Data “known” to agent

- At each point in run, each agent knows
  - All the data provided by initial conditions
    - Public keys, a private key, shared secret key, …
  - All the data generated by that agent
    - Fresh nonces chosen at random, new keys, …
  - All the messages received
  - Any data derivable from this information
    - Can decrypt a message if decryption key known

Symbolic representation of data and symbolic characterization of “data knowledge” is called “the Dolev-Yao model.”

Protocol correctness



Correct if no security violation in any run

Correctness conditions

- Authentication
  - Idea: "I know I am talking to you"
  - Formalization 1
    - If Alice initiates conversation by sending to Bob, then data she receives was generated by Bob for Alice.
  - Formalization 2
    - If Alice completes the initiator role, sending messages to Bob, then Bob completes the responder role with the same messages in the same order.
    - One-to-one correspondence between sessions
  - Your thoughts and alternatives?

Correctness conditions

- Secrecy
  - Idea: "The attacker does not know our secrets"
  - Formalization 1
    - The session key cannot be computed from the data available to the attacker.
  - Formalization 2
    - The entire conversation between Alice and Bob is indistinguishable (to others) from a run with completely different nonces, keys, etc.
  - Your thoughts and alternatives?

Safety vs Liveness

- Trace property
  - Property is true of a system iff it is true for all traces (runs) of the system
- Safety property
  - Bad things do not happen
  - Examples: no deadlock, no page fault, …
- Liveness property
  - Good things do happen (eventually)
  - Example: every process gets scheduled to run

Safety vs Liveness

- Safety property
  - "Bad things do not happen"

    $\forall$ traces t, possibly infinite:
    $P(t)$ iff $\forall t' < t.\ P(t')$

  - If a safety property fails, it fails at some finite point
- Liveness property
  - "Good things do happen (eventually)"

    $\forall$ finite initial traces s: $\exists$ trace t. $P(st)$

  - A liveness property holds if every beginning of a trace can be extended to one with the desired property

Contract Signing

- Two parties want to sign a contract
  - Multi-party signing is more complicated
- The contract is known to both parties
  - The protocols we will look at are *not* for contract negotiation (e.g., auctions)
- The attacker could be
  - Another party on the network
  - The "person" you think you want to sign a contract with

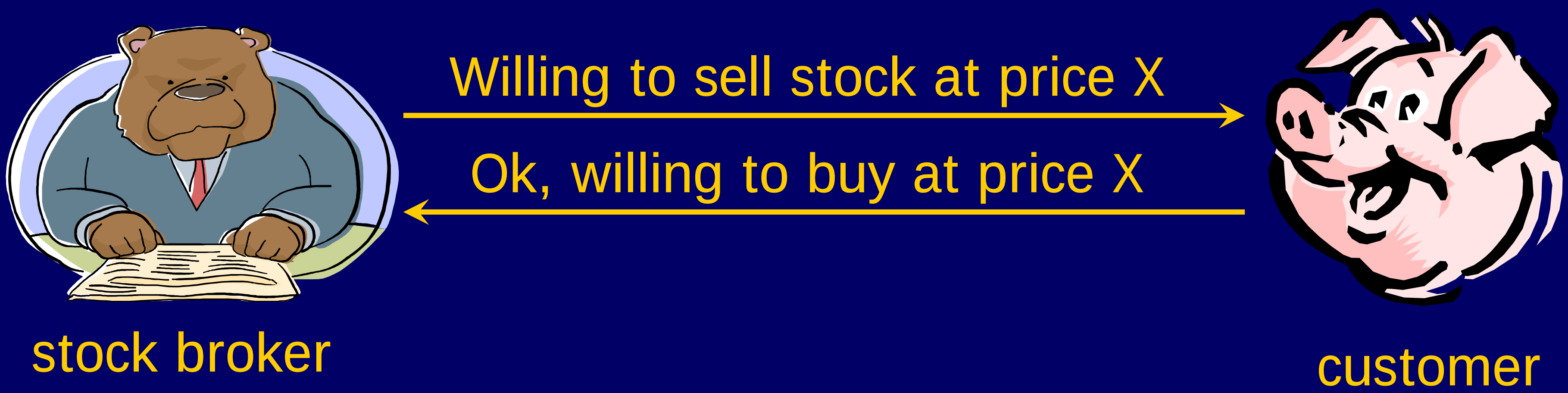
Example

Seller advertises and receives bids

Buyer may have several choices

- Both parties want to sign a contract
- Neither wants to commit first

Another example: stock trading



- Why signed contract?
  - Suppose market price changes
  - Buyer or seller may want proof of agreement

Network is Asynchronous

- Physical solution
  - Two parties sit at table
  - Write their signatures simultaneously
  - Exchange copies
- Problem
  - How to sign a contract on a network?

Fair exchange: general problem of exchanging information so both succeed or both fail

Fundamental limitation

- Impossibility of consensus
  - *Very weak consensus is not solvable if one or more processes can be faulty*
- Asynchronous setting
  - Process has *initial* 0 or 1, and eventually *decides* 0 or 1
  - *Weak termination*: some correct process decides
  - *Agreement*: no two processes decide on different values
  - *Very weak validity*: there is a run in which the decision is 0 and a run in which the decision is 1
- Reference
  - M. J. Fischer, N. A. Lynch and M. S. Paterson, *Impossibility of Distributed Consensus with One Faulty Process*. J ACM 32(2):374-382 (April 1985).

Implication for fair exchange

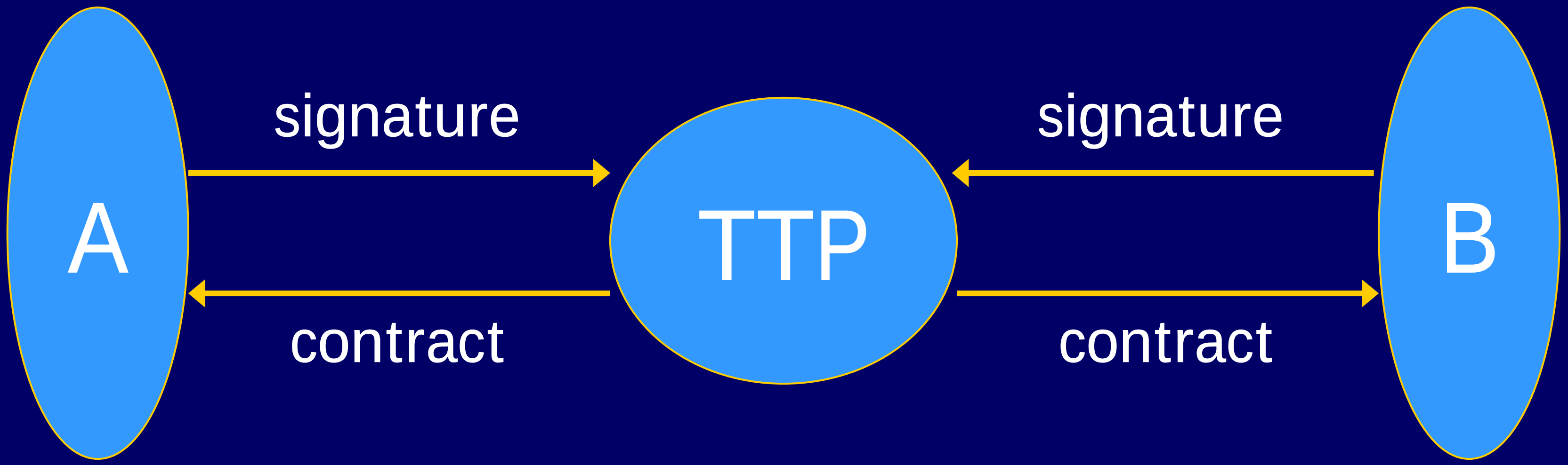
- Need a trusted third party (TTP)
  - It is impossible to solve strong fair exchange without a trusted third party.

    The proof is by relating strong fair exchange to the problem of consensus and adapting the impossibility result of Fischer, Lynch and Paterson.
- Reference
  - H. Pagnia and F. C. Gärtner, On the impossibility of fair exchange without a trusted third party. Technical Report TUD-BS-1999-02, Darmstadt University of Technology, March 1999

Two forms of contract signing

- Gradual-release protocols
  - Alice and Bob sign contract
  - Exchange signatures a few bits at a time
  - Issues
    - Signatures are verifiable
    - Work required to guess remaining signature decreases
    - Alice, Bob must be able to verify that what they have received so far is part of a valid signature
- Add trusted third party

Easy TTP contract signing

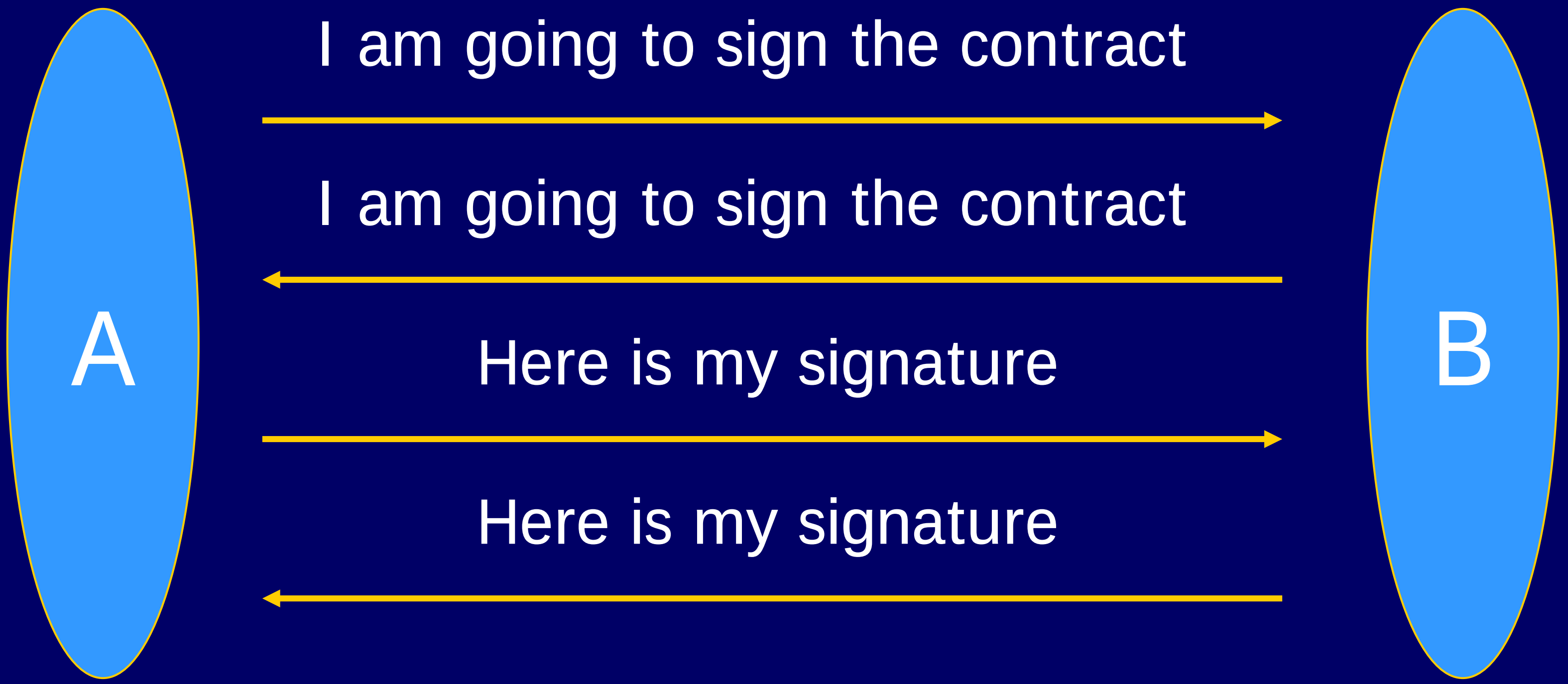


- Problem
  - TTP is bottleneck
  - Can we do better?

Optimistic contract signing

- Use TTP only if needed
  - Can complete contract signing without TTP
  - TTP will make decisions if asked
- Goals
  - Fair: no one can cheat the other
  - Timely: no one has to wait indefinitely (assuming that TTP is available)
  - Other properties …

A general protocol outline

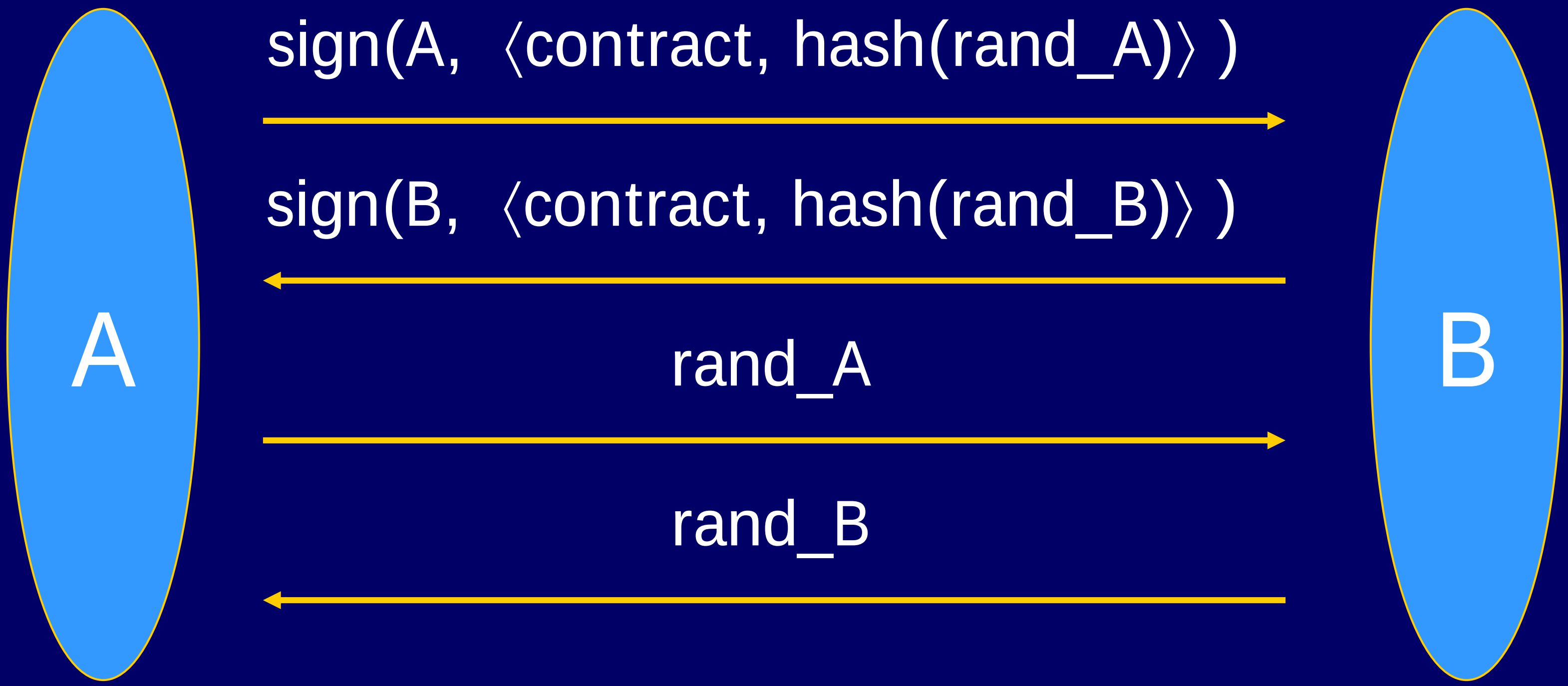


- Trusted third party can force contract
  - Third party can declare contract binding if presented with first two messages.

Commitment (idea from crypto)

- Cryptographic hash function
  - Easy to compute function f
  - Given f(x), hard to find y with f(y)=f(x)
  - Hard to find pairs x, y with f(y)=f(x)
- Commit
  - Send f(x) for randomly chosen x
- Complete
  - Reveal x

Refined protocol outline



- Trusted third party can force contract
  - Third party can declare contract binding by signing first two messages.

Optimistic Protocol [Asokan, Shoup, Waidner]

Input:
PK_A, T, text

Input:
PK_B, T, text

A

B

$\mathbf{m_1} = sig_A(PK_A, PK_B, T, \text{text}, hash(R_A))$ (A → B)

$\mathbf{m_2} = sig_B(\mathbf{m_1}, hash(R_B))$ (B → A)

$\mathbf{m_3} = R_A$ (A → B)

$\mathbf{m_4} = R_B$ (B → A)

$\mathbf{m_1}, R_A, \mathbf{m_2}, R_B$

Asokan-Shoup-Waidner Outcomes

- Contract from normal execution

  $\mathbf{m_1}$, R_A, $\mathbf{m_2}$, R_B

- Contract issued by third party

  $sig_T(\mathbf{m_1}, \mathbf{m_2})$

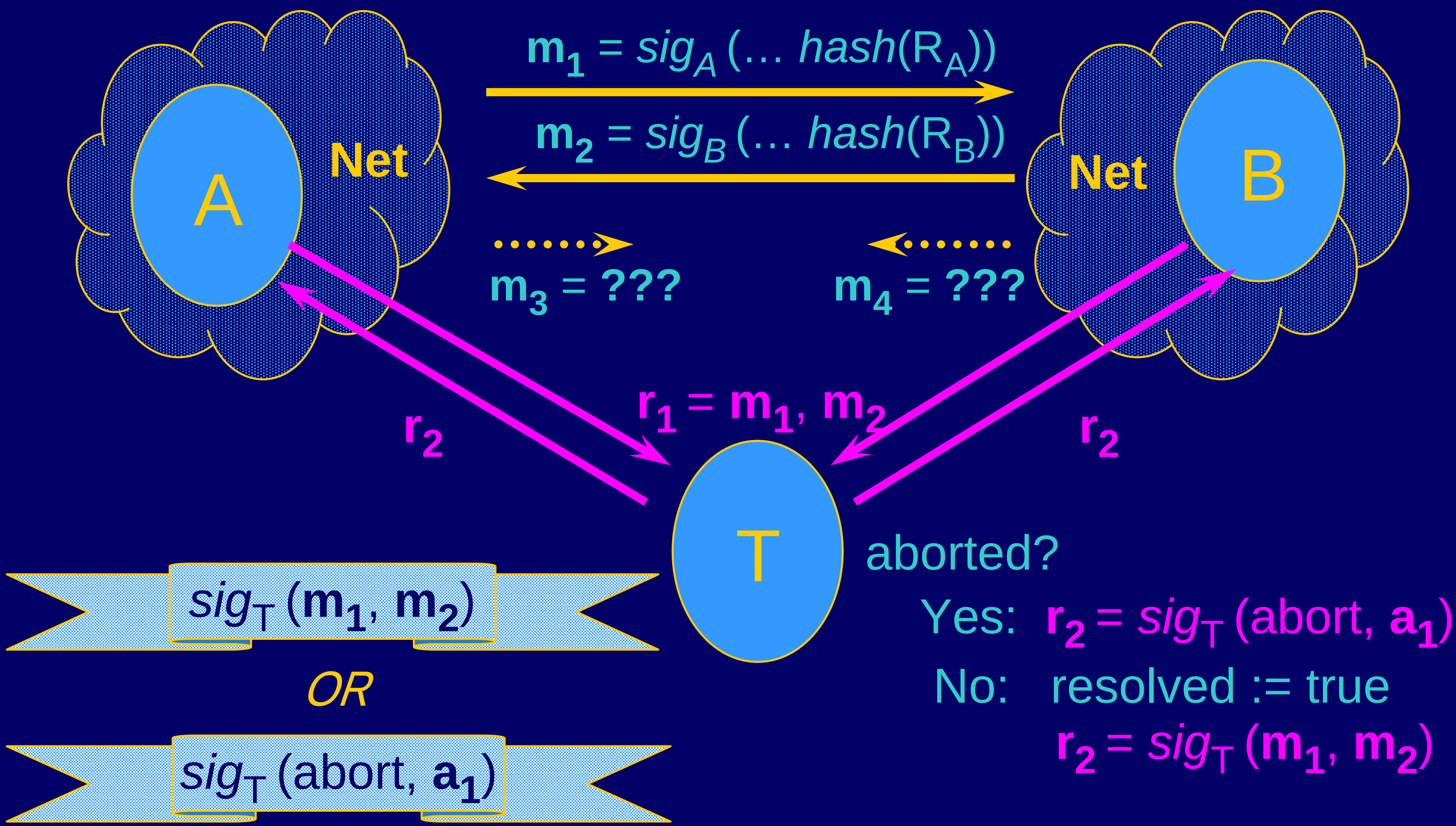
- Abort token issued by third party

  $sig_T(\text{abort}, \mathbf{a_1})$

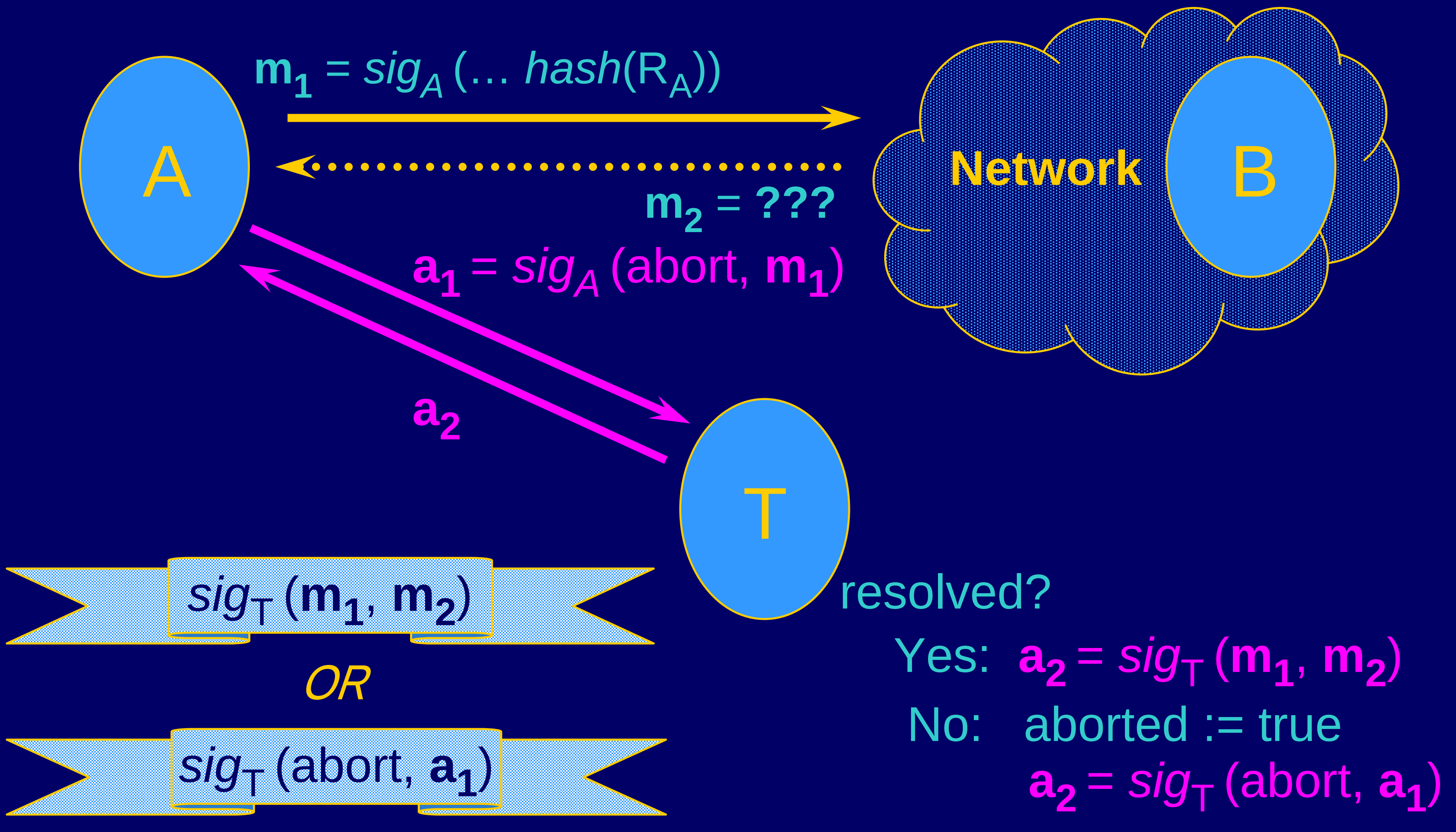
Role of Trusted Third Party

- T can issue a replacement contract
  - Proof that both parties are committed
- T can issue an abort token
  - Proof that T will not issue contract
- T acts only when requested
  - decides whether to abort or resolve on the first-come-first-serve basis
  - only gets involved if requested by A or B

Resolve Subprotocol



Abort Subprotocol



Fairness and Timeliness

Fairness

If A cannot obtain B's signature, then
B should not be able to obtain A's signature

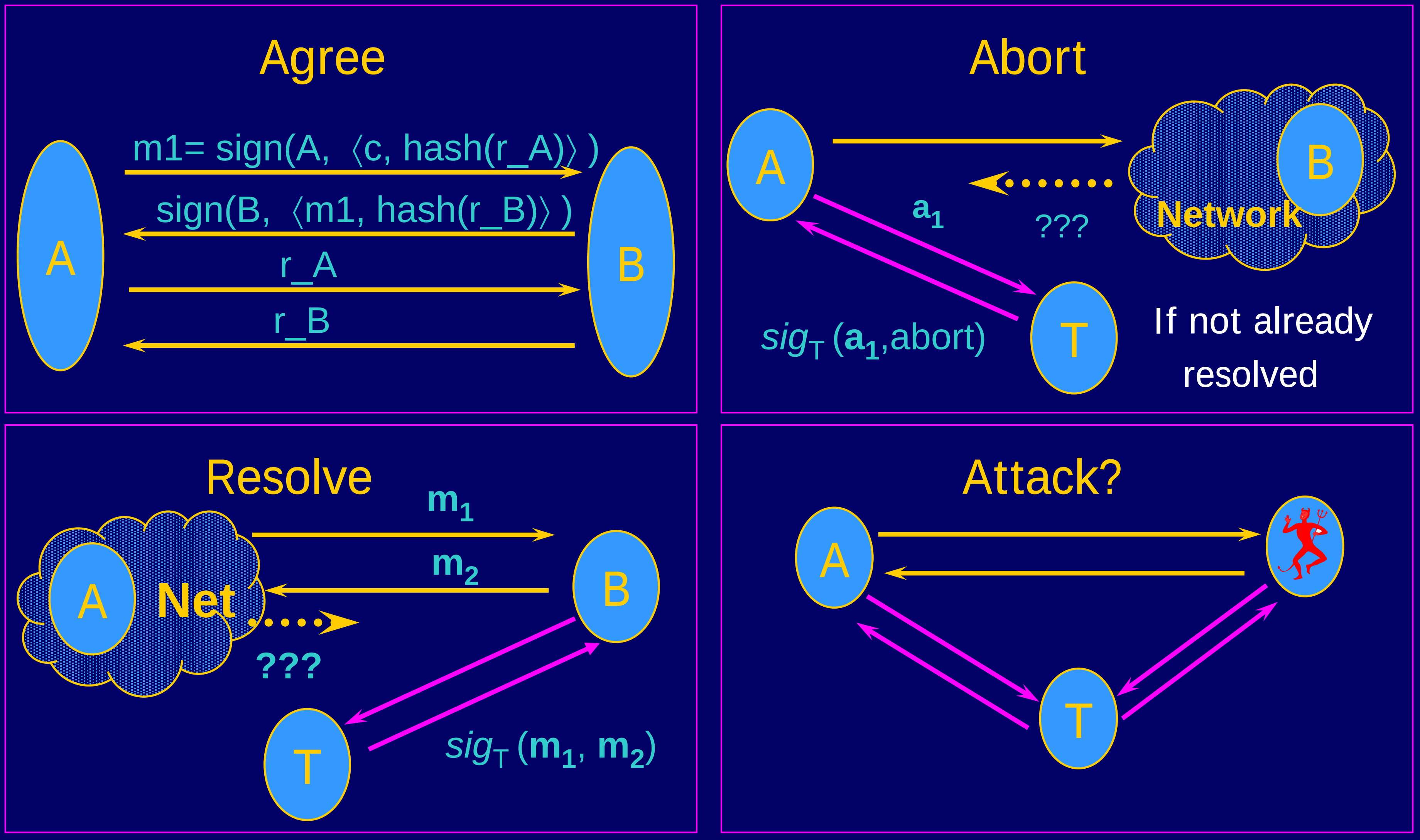
and vice versa

Timeliness

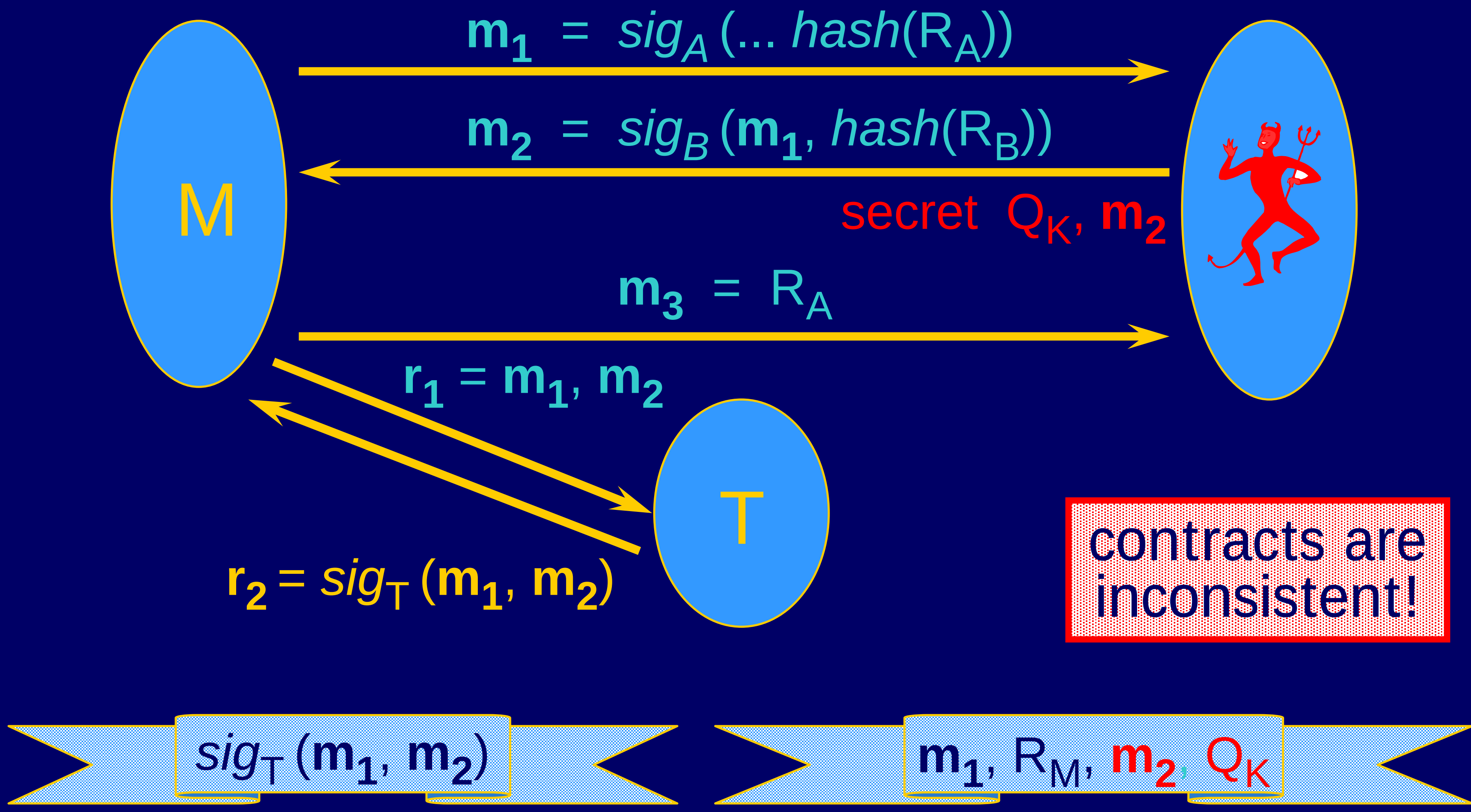
"One player cannot force the other to wait --
a fair and timely termination can always be
forced by contacting TTP"

[Asokan, Shoup, Waidner Eurocrypt '98]

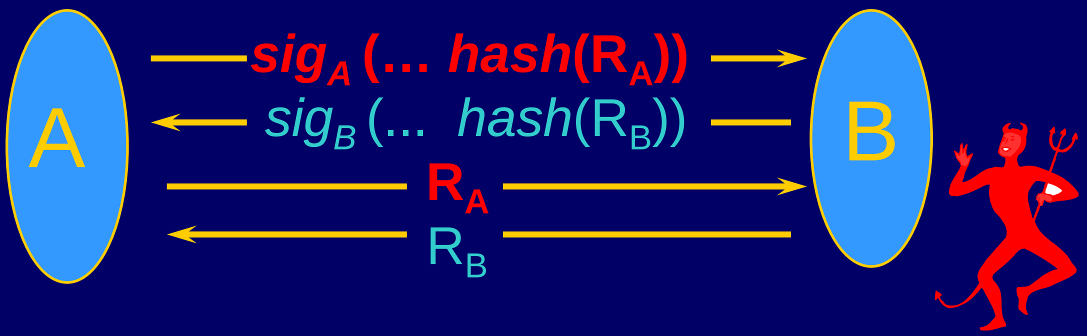
Asokan-Shoup-Waidner protocol



Contract Consistency Attack

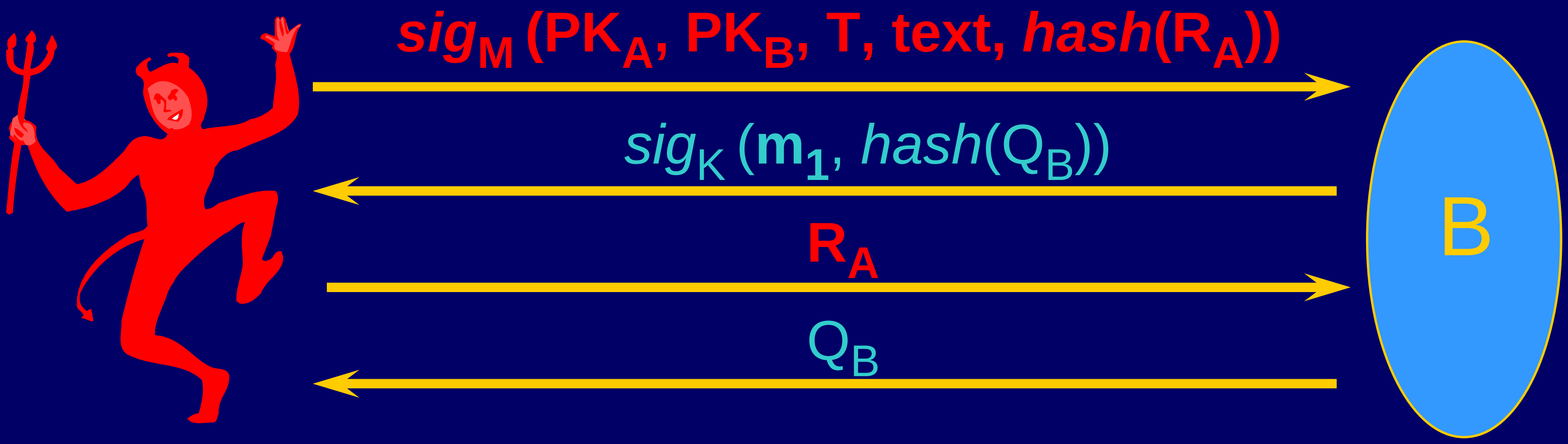


Replay Attack

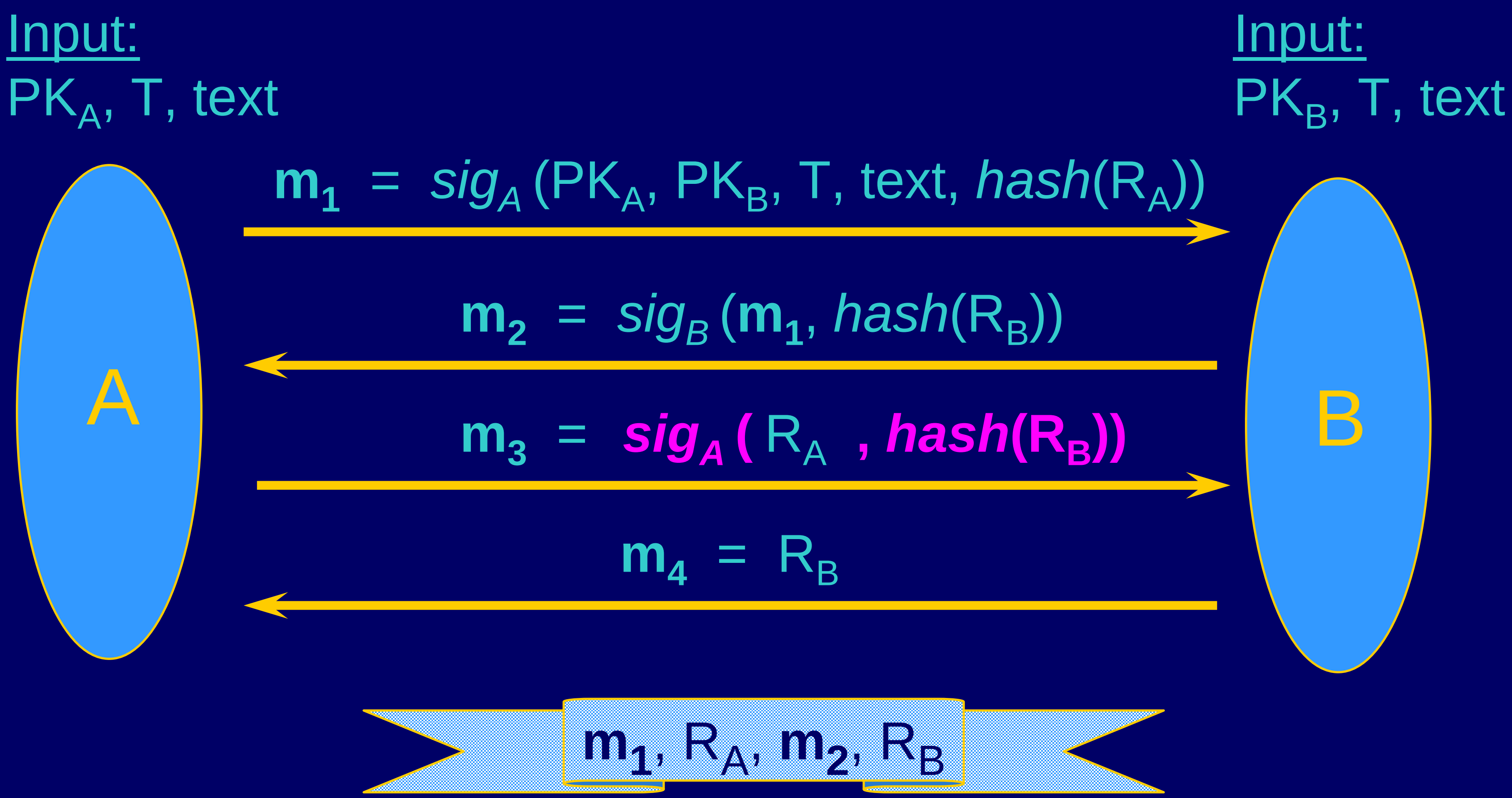


Intruder causes B to commit to old contract with A

Later ...



Fixing the Protocol

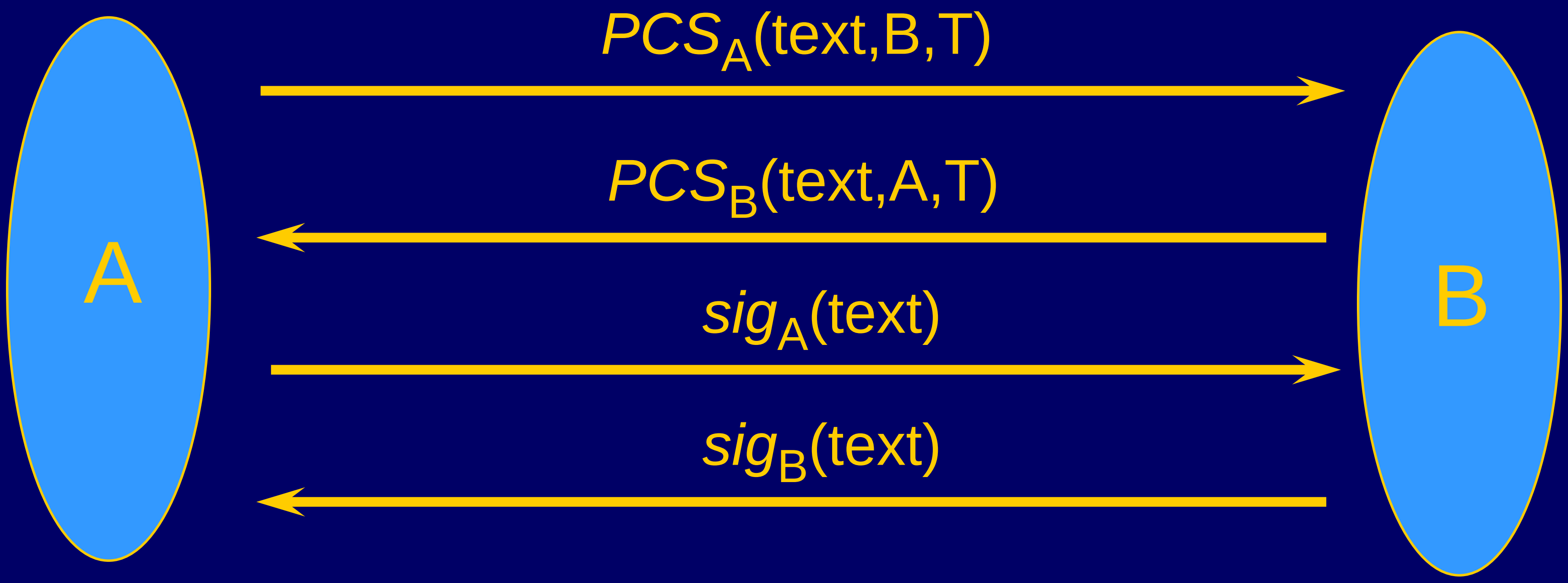


Desirable properties

- Fair
  - If one can get contract, so can other
- Accountability
  - If someone cheats, message trace shows who cheated
- Abuse free
  - No party can show that they can determine outcome of the protocol

Abuse-Free Contract Signing

[Garay, Jakobsson, MacKenzie]



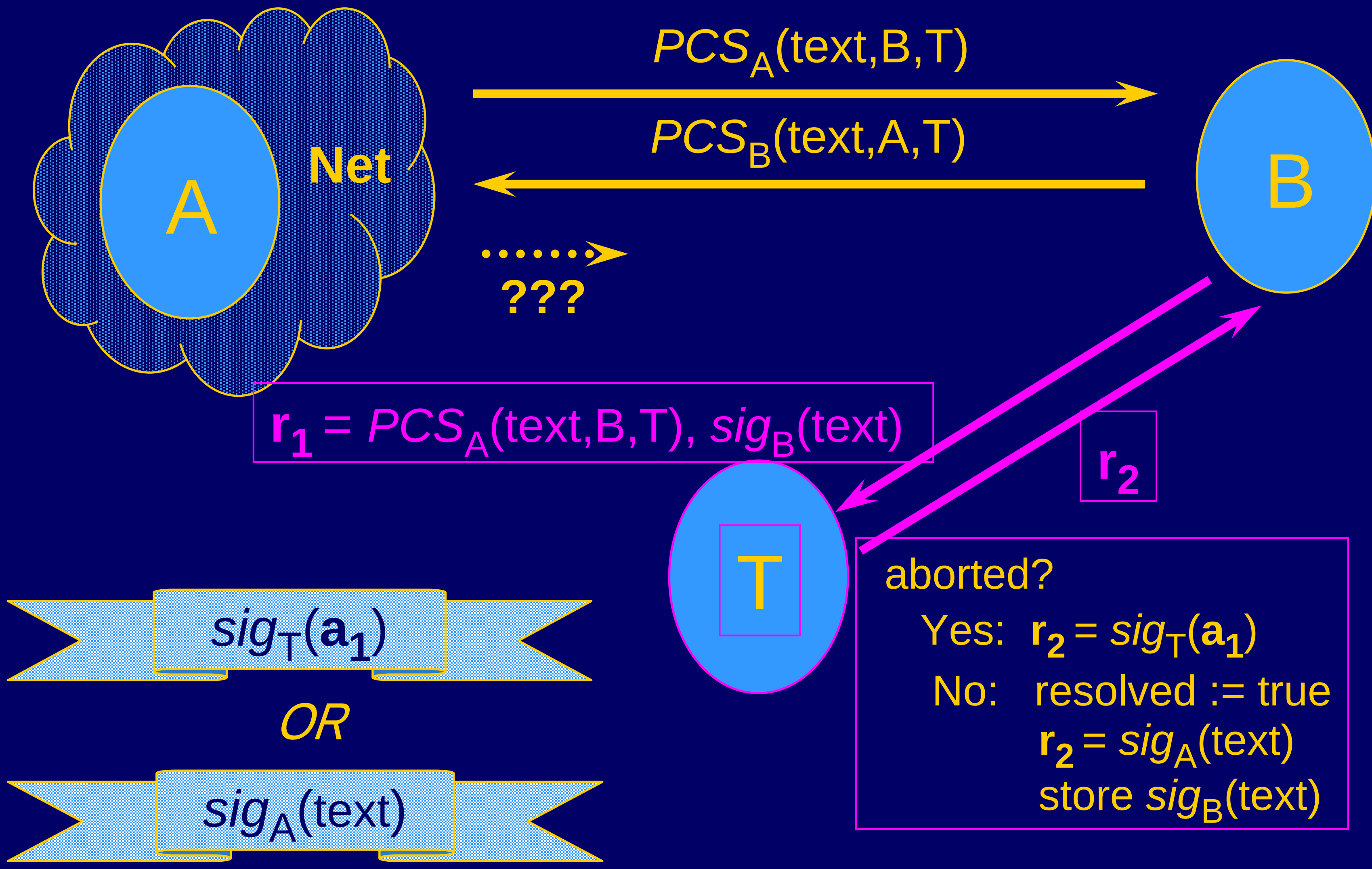
Preventing “abuse” [Garay, Jakobsson, MacKenzie]

- Private Contract Signature
  - Special cryptographic primitive
  - B cannot take msg from A and show to C
  - T converts signatures, does not use own

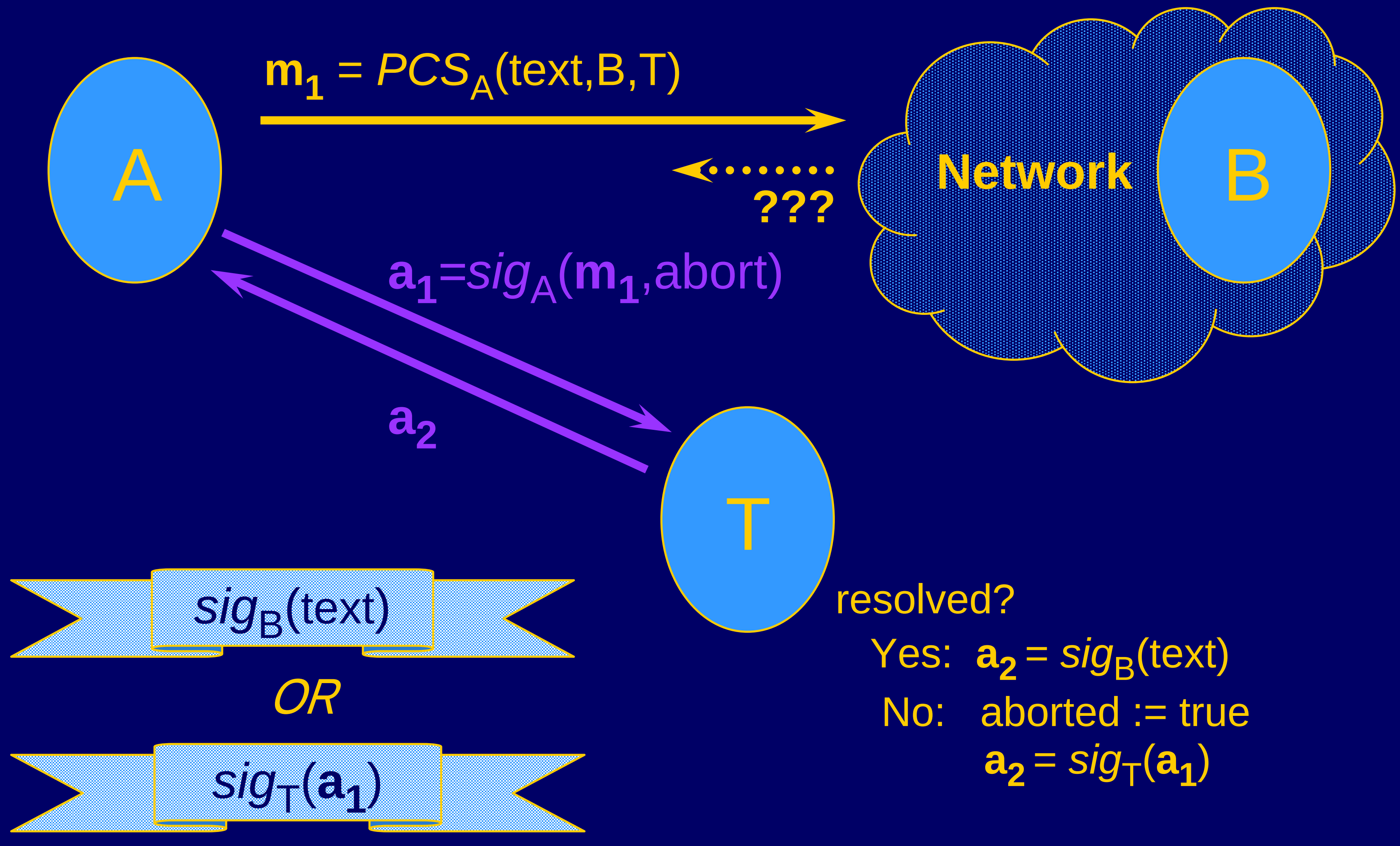
Role of Trusted Third Party

- T can convert PCS to regular signature
  - Resolve the protocol if necessary
- T can issue an abort token
  - Promise not to resolve protocol in future
- T acts only when requested
  - decides whether to abort or resolve on a first-come-first-served basis
  - only gets involved if requested by A or B

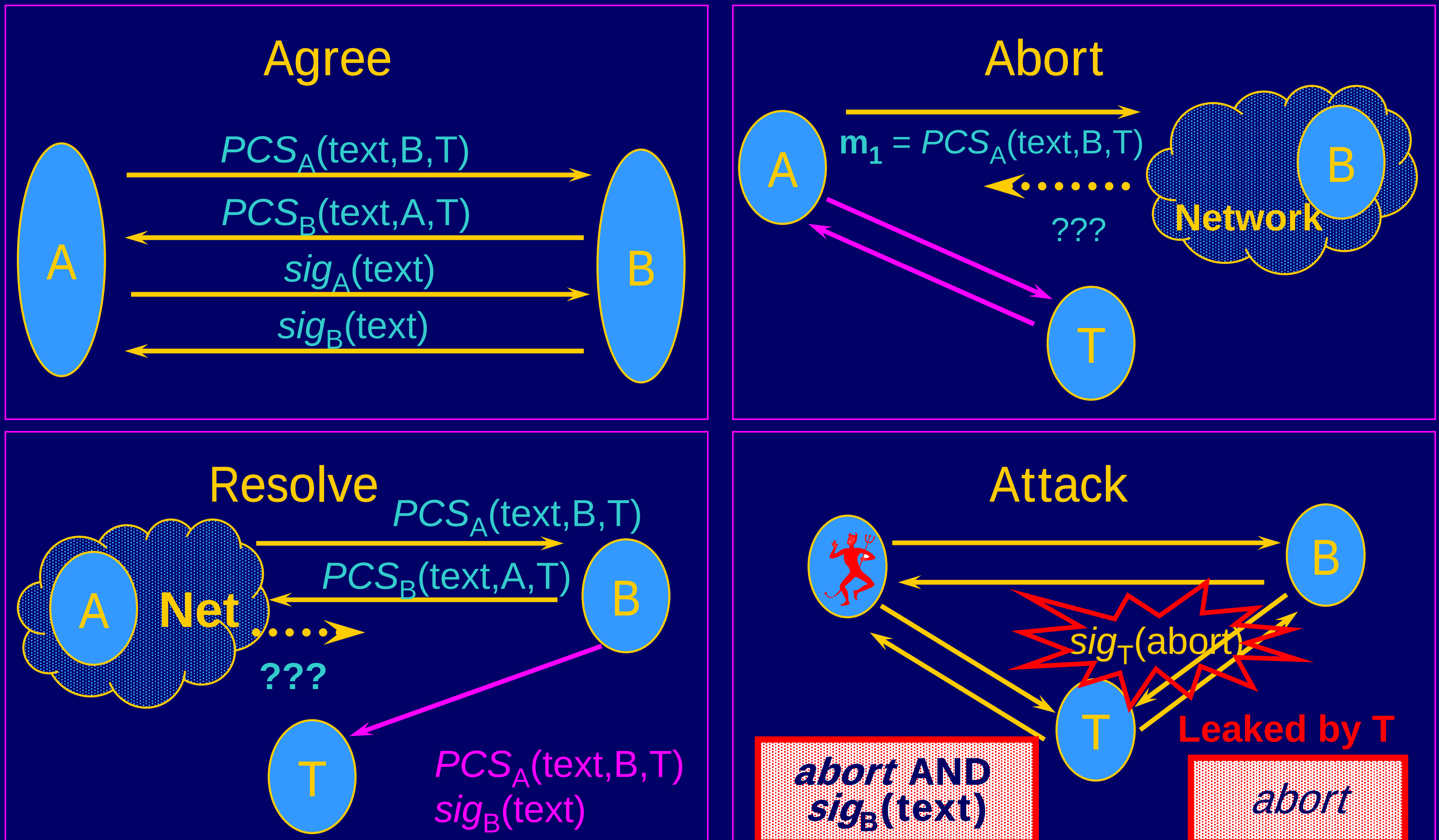
Resolve Subprotocol



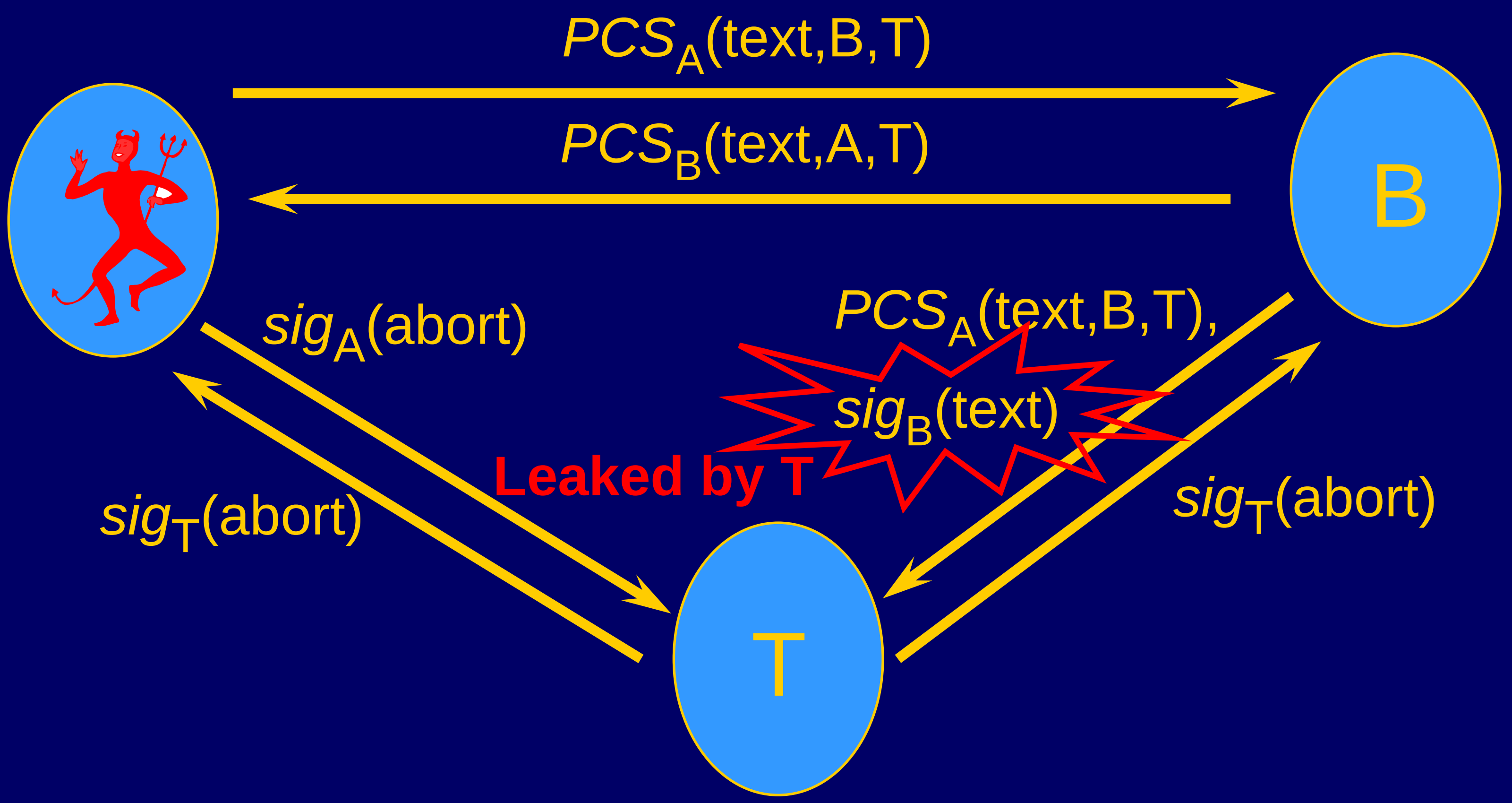
Abort Subprotocol



Garay, Jakobsson, MacKenzie



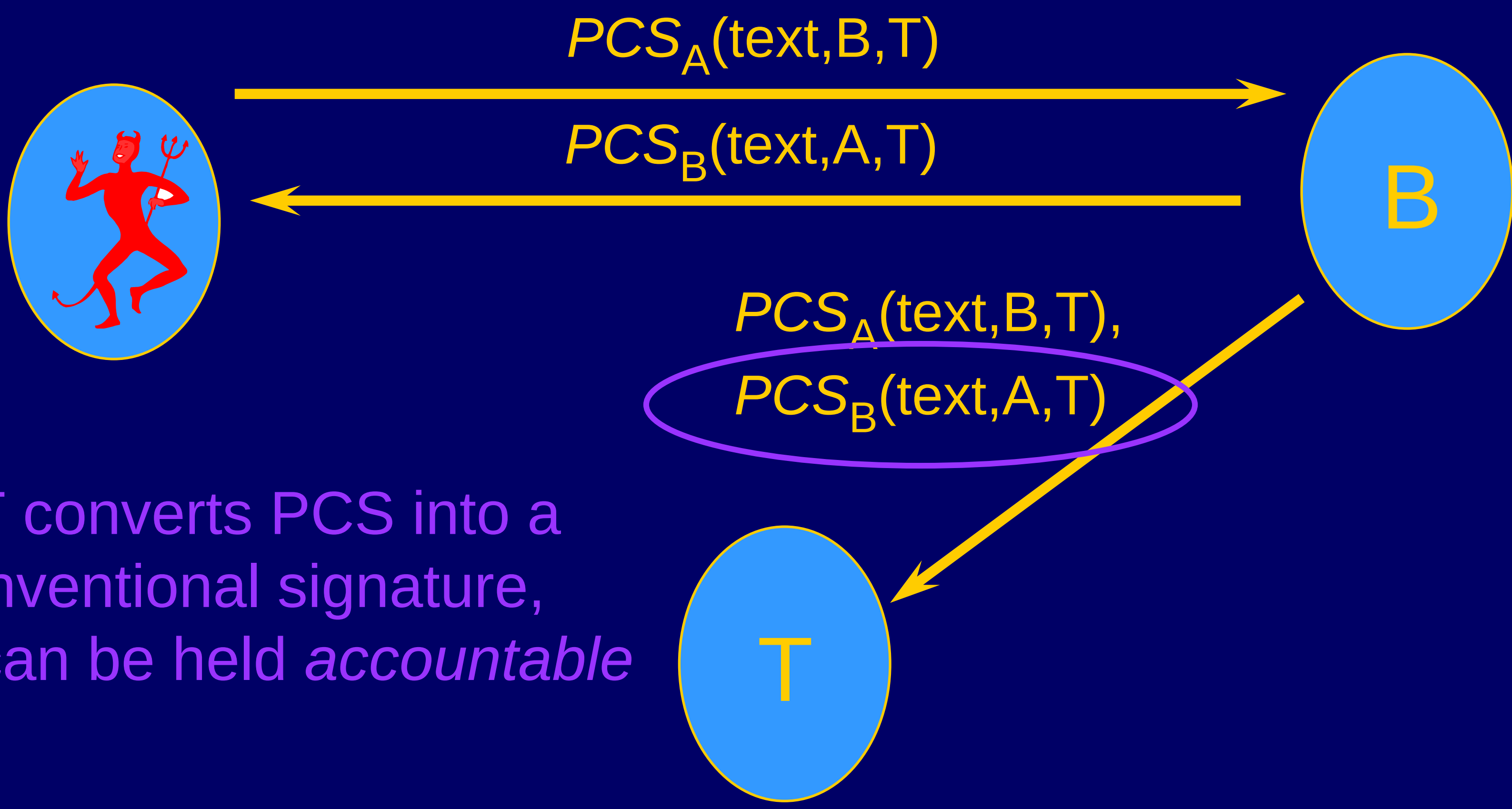
Attack



abort AND sig_B(text)

only *abort*

Repairing the Protocol



If T converts PCS into a conventional signature, T can be held *accountable*

Balance

No party should be able to **unilaterally** determine the outcome of the protocol

Balance may be violated even if basic fairness is satisfied!

Stock sale example: there is a point in the protocol where the broker can <u>unilaterally</u> choose whether the sale happens or not

Can a timely, optimistic protocol be fair AND balanced?

Advantage

Willing to sell stock at price X →

← Ok, willing to buy at price X

Must be able to ask TTP to cancel this instance of protocol, or will be stuck indefinitely if customer does not respond

stock broker

customer

Can go ahead and complete the sale, OR
can still ask TTP to cancel
(TTP doesn’t know customer has responded)

Optimistically waits for broker to respond …

Chooses whether deal will happen:
does not have to commit stock for sale,
can cancel if sale looks unprofitable

Cannot back out of the deal:
must commit money for stock

"Abuse free": as good as it gets

- Specifically:
  - One signer always has an advantage over the other, no matter what the protocol is
  - Best case: signer with advantage cannot *prove* it has the advantage to an outside observer

Theorem

- In any fair, optimistic, timely contract-signing protocol, if one player is optimistic*, the other player has an advantage.

* optimistic player: waits a little before going to the third party

Abuse-Freeness

~~Balance~~ impossible ☹

~~No party should be able to unilaterally determine the outcome of the protocol~~

Abuse-Freeness

No party should be able to **prove** that it can unilaterally determine the outcome of the protocol

How to prove something like this?

- Define "protocol"
  - Program for Alice, Bob, TTP
  - Each move depends on
    - Local State (what's happened so far)
    - Message from network
    - Timeout
- Consider possible optimistic runs
- Show someone gets advantage

Key idea (omitting many subtleties)

- Define "power" of a signer (A or B) in a state s

$$\text{Power}_A(s) = \begin{cases} 2 & \text{if A can get contract by reading a message already in network, doing internal computation} \\ 1 & \text{if A can get contract by communicating with TTT, assuming B does nothing} \\ 0 & \text{otherwise} \end{cases}$$

- Look at *optimistic* transition $s \rightarrow s'$ where $\text{Power}_B(s') = 1 > \text{Power}_B(s) = 0$.

Advantage (intuition for main argument)

- If $\text{Power}_B(s) = 0 \rightarrow \text{Power}_B(s') = 1$ then
  - This is result of some move by *A*
    - $\text{Power}_B(s) = 0$ means B cannot get contract without B's help
  - The move by *A* is not a message to TTP
    - The proof is for an *optimistic* protocol, so we are thinking about a run without msg to T
  - B could abort in state s
    - We assume protocol is timely and fair: B must be able to do something, cannot get contract
  - B can still abort in s', so B has advantage!

Conclusions

- Online contract signing is subtle
  - Fair
  - Abuse-free
  - Accountability
- Several interdependent subprotocols
  - Many cases and interleavings
- Finite-state tools great for case analysis!
  - Find bugs in protocols proved correct
- Proving properties of all protocols is harder
  - Understand what is possible and what is not