Programming Language Foundations for Distributed Systems

Ankush Das

Applied Scientist, Amazon AWS

Imperial College, London

March 6, 2023

We are Living in a Distributed Age!

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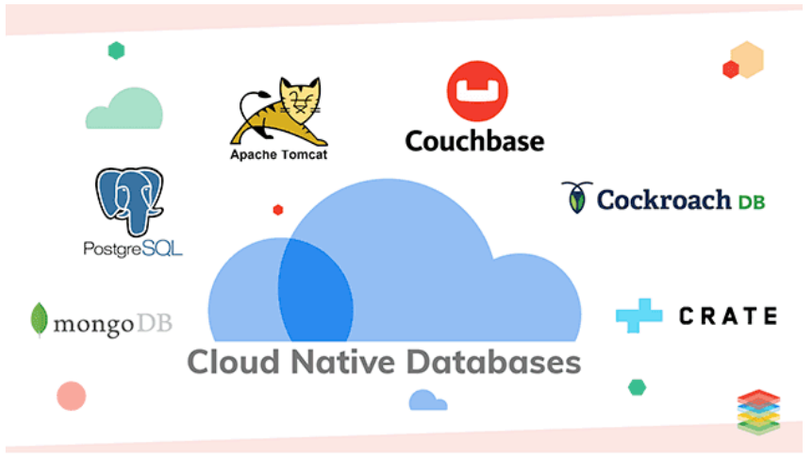

Programming in the Distributed Age is Hard!

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Software Bugs

DAILY NEWS

Blackout hits New York City and the Northeast in 2003

A software bug known as a race condition

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Performance Defects

The Washington Post
Democracy Dies in Darkness

HealthCare.gov

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techradar pro

Microsoft Azure bug left a bunch of cloud databases wide open

By Sead Fadilpašić published April 29, 2022

Domain-Specific Issues

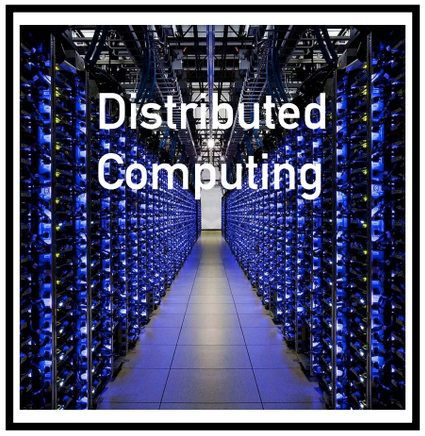
TechRepublic

Report: Software failure caused $1.7 trillion in financial losses in 2017

ACM DL DIGITAL LIBRARY

What Bugs Live in the Cloud? A Study of 3000+ Issues in Cloud Systems

How can PL Tools Help?



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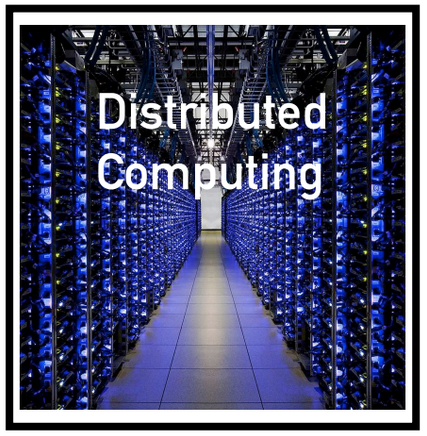

The Software Model Checker
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CPA✓

CBMC

Model Checkers

Boogie: An Intermediate
Verification Language

Dafny

Z3

VIPER

Verification
Languages

LiquidHaskell

$\Gamma \vdash e : \tau$

Type Systems

The Coq
Proof Assistant

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Proof Assistants

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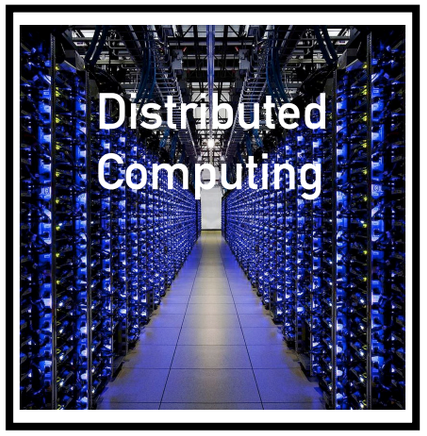

Concurrency Reasoning

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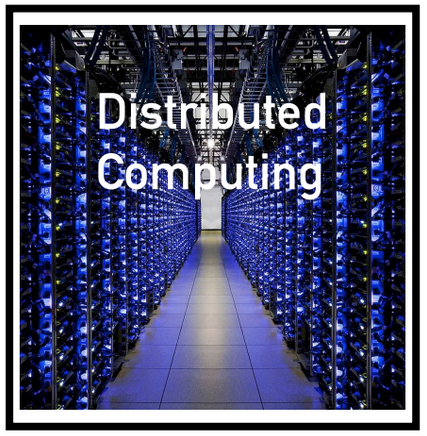

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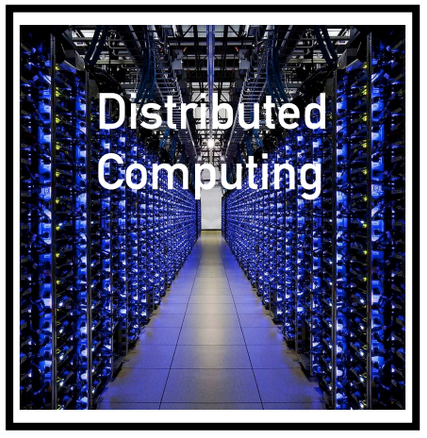

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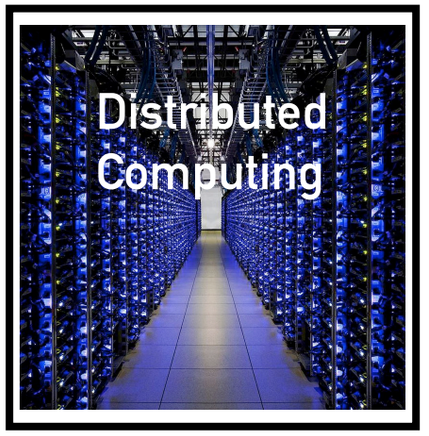

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Domain-Specific Support

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Type system for concurrent message-passing programs

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Resource-Aware Session Types

[LICS '18, SAS '20, CSF '21]

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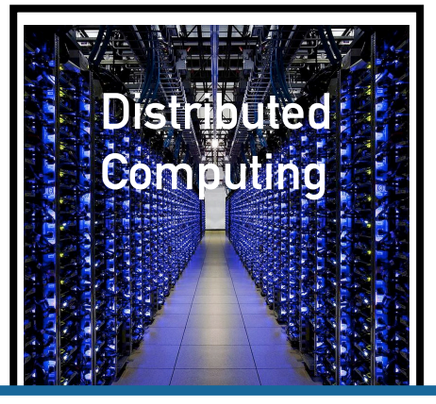

Performance & Verification

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Type system for concurrent message-passing programs

What are Session Types?

- Session types are a system for concurrent message-passing programs
- Communication via typed bi-directional channels
- Session type governs the type and direction of message exchanges

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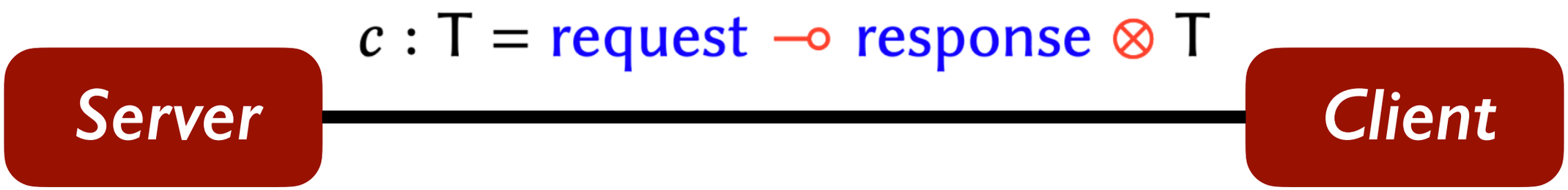

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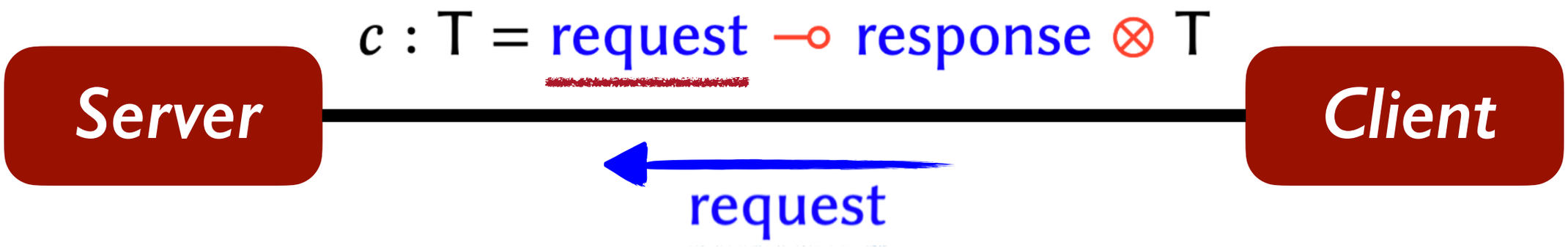

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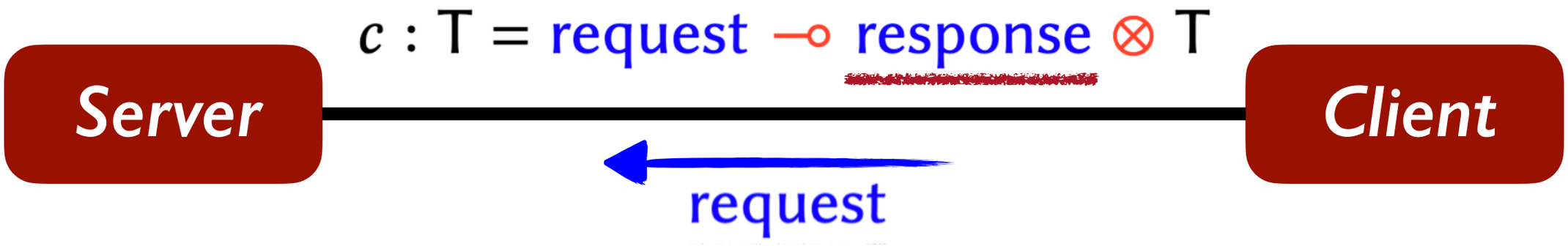

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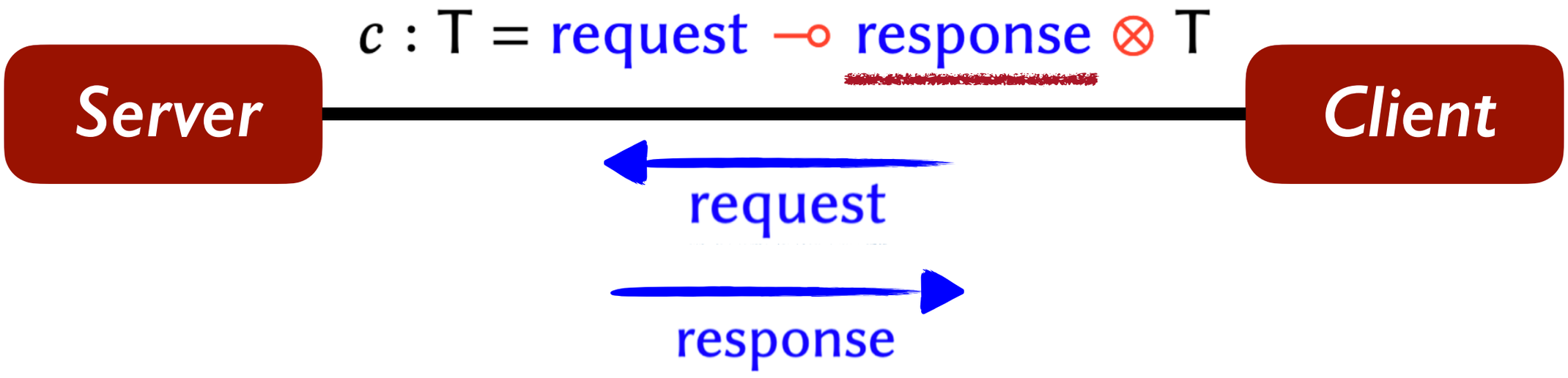

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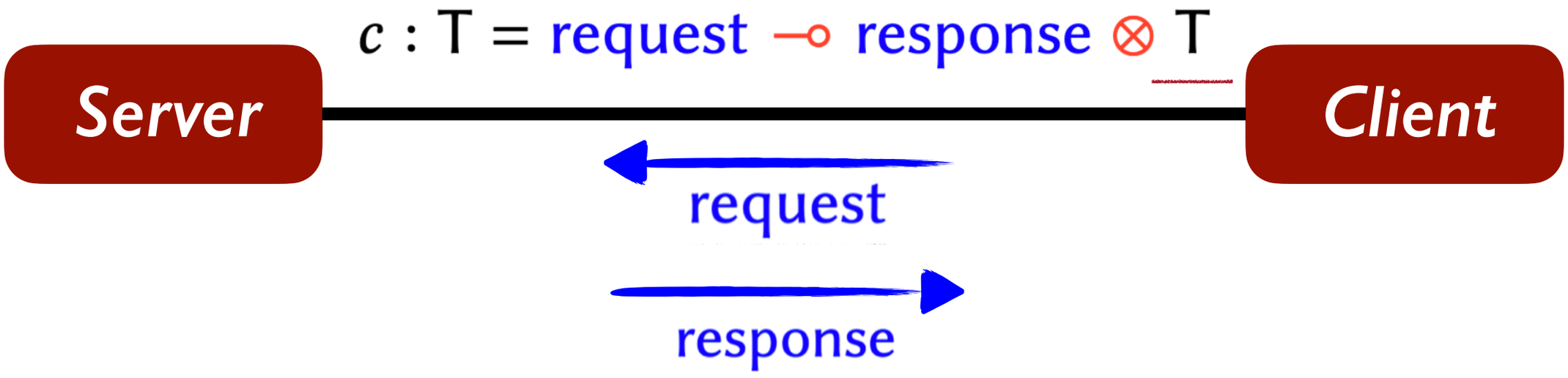

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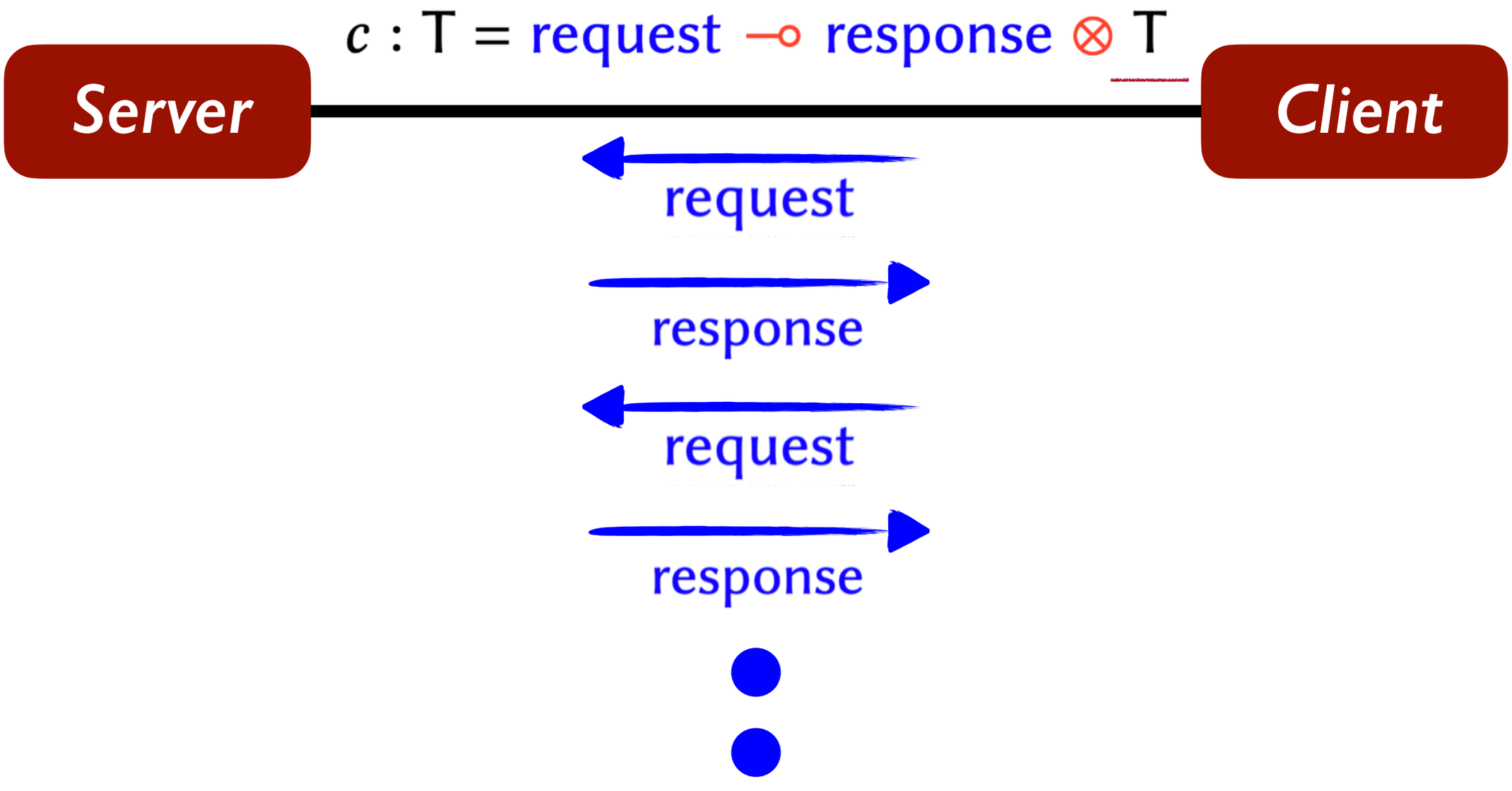

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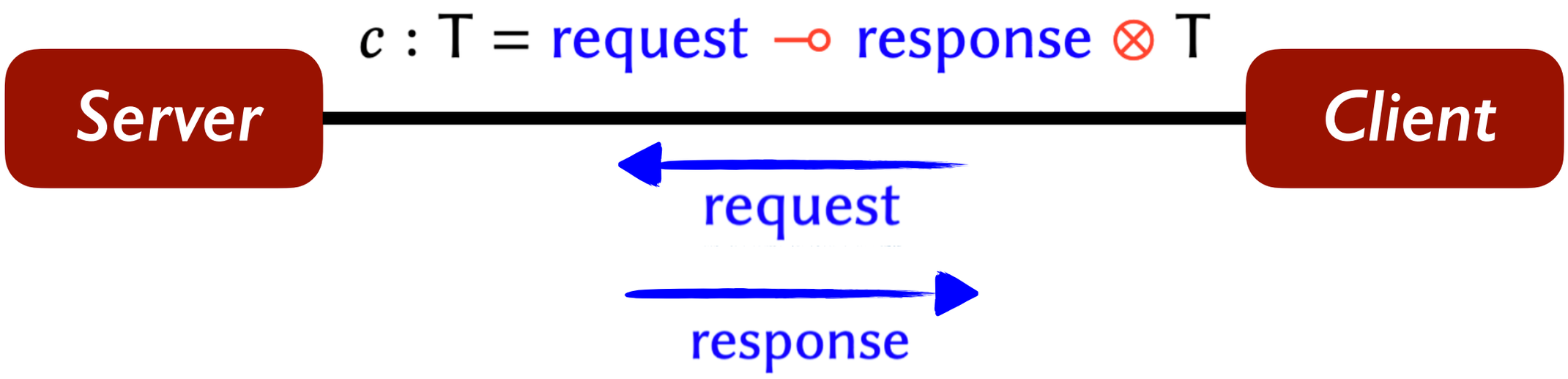

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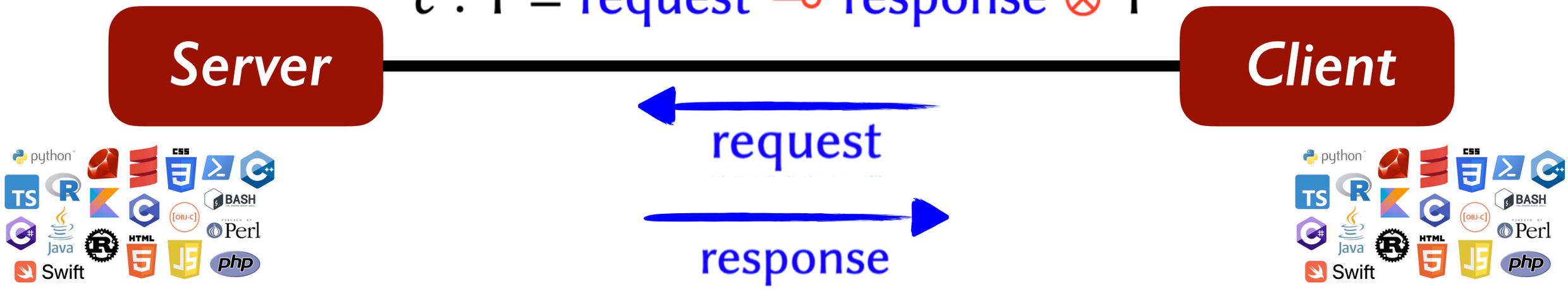
$$c : \mathsf{T} = \text{request} \multimap \text{response} \otimes \mathsf{T}$$



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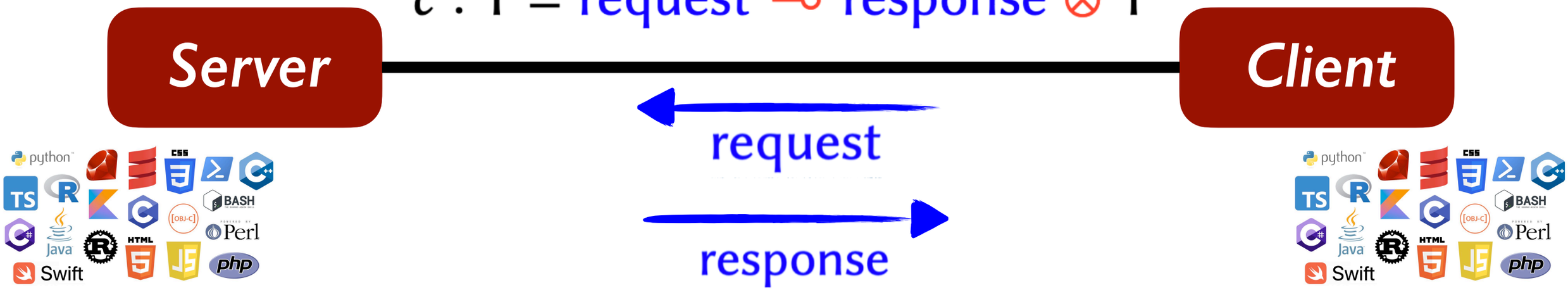

✓ *Communication Safety*

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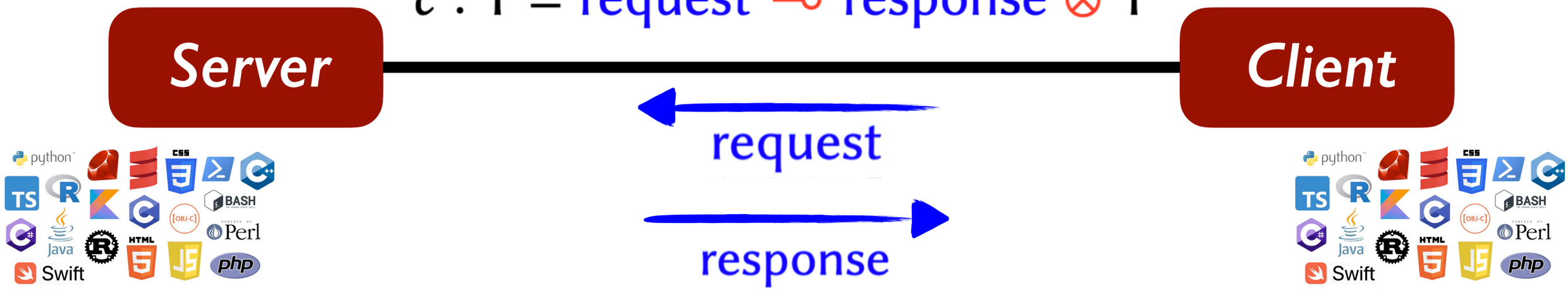

- ✓ *Communication Safety*
- ✓ *Type acts as Specification*

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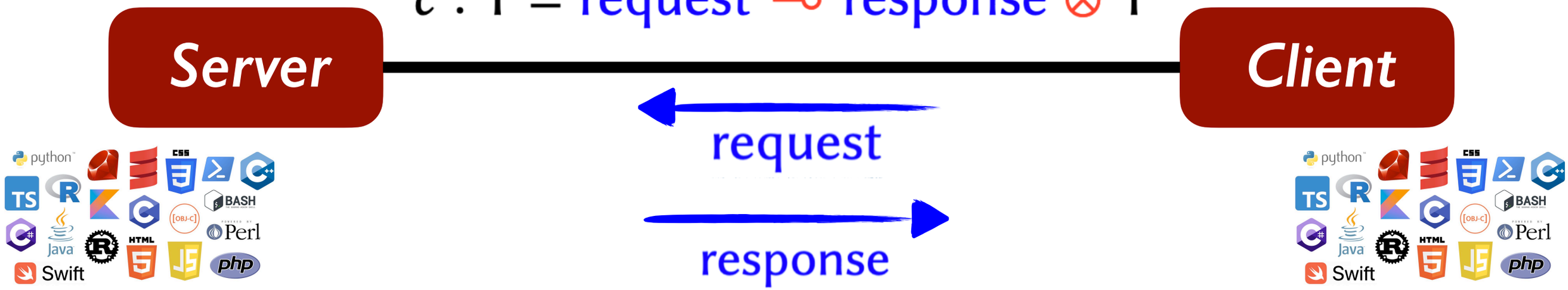

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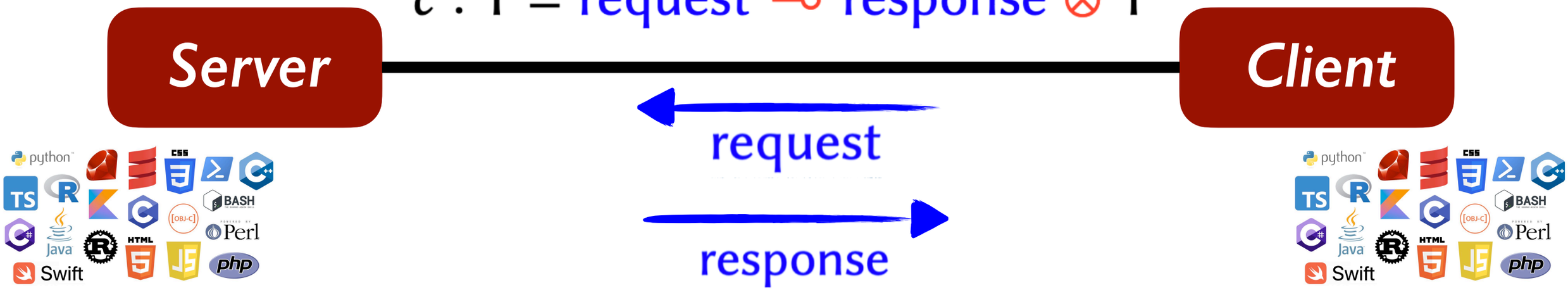

- *Communication Safety*
- *Type acts as Specification*
- *Compositionality & Modularity*
- *Deadlock & Livelock Freedom!*

Talk Outline

Protocol Enforcement & Asset Preservation

Probabilistic Reasoning

Performance & Verification

Nomos

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Smart Contracts

Programs that implement a digital (legal or financial) transaction

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Online Transactions

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Betterment
wealthfront
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Wealth Management Applications

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recently popularized in the form of

wealthfront
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Wealth Management Applications

Blockchains and Cryptocurrencies

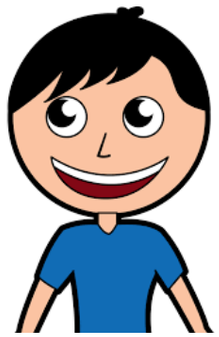
Example: Auction Contract

status: running

Example: Auction Contract

Bidder 1

Bid 1

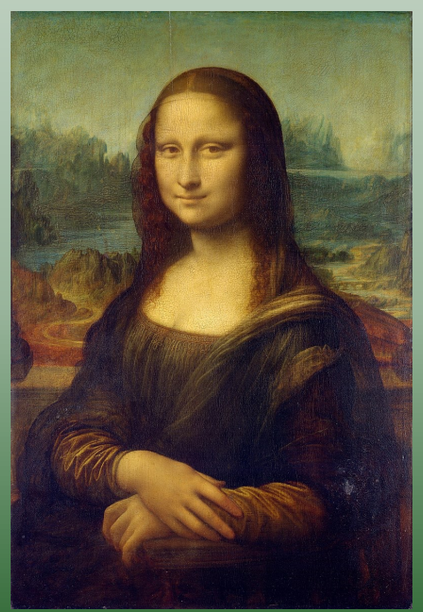


Bidder 2

Bid 2

Bidder 3

Bid 3



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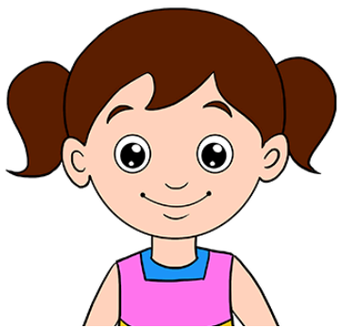

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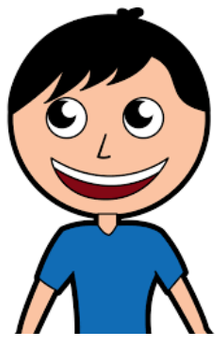

Bidder 2

Bidder 3

Bid 1

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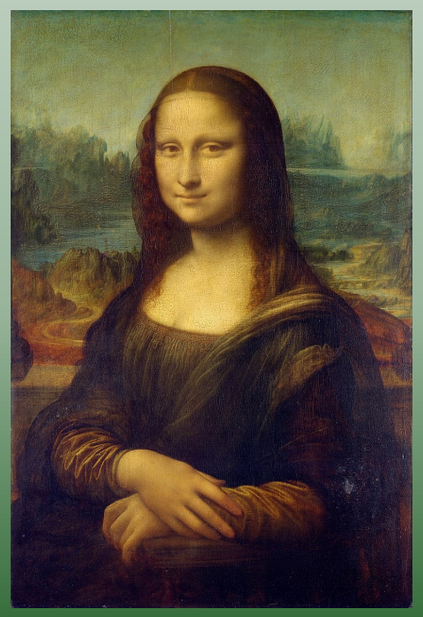

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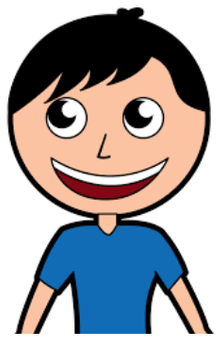

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Bid 3

status: ended

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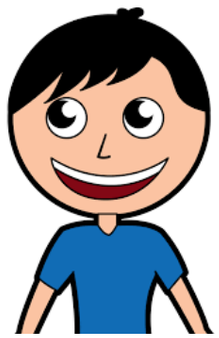

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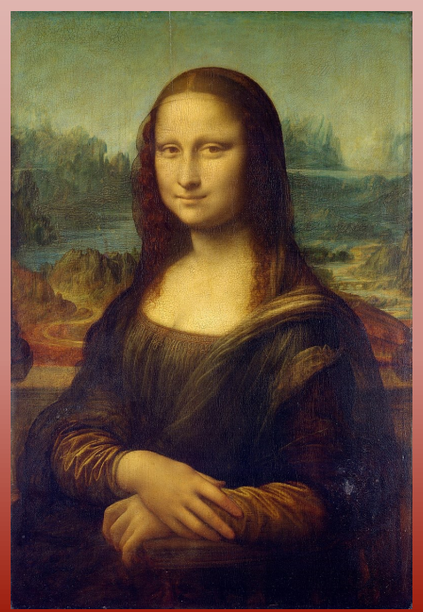

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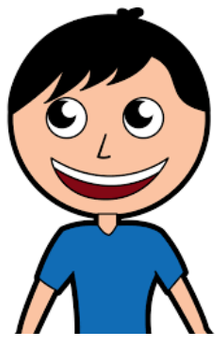

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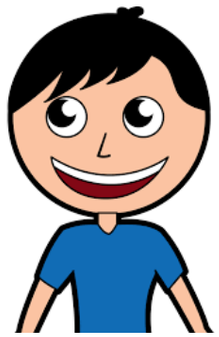

Bidder 2

Bid 2

Bidder 3

Bid 3 ✓

status: ended

Auction in Solidity


```
function bid() public payable {
    uint bid = msg.value;                  // bidder's bid
    address bidder = msg.sender;           // bidder's address
    pendingReturns[bidder] = bid;          // store in local dictionary
    if (bid > highestBid) {                // update highest bidder & bid
        highestBidder = bidder;
        highestBid = bid;
    }
}

function collect() public {
    // highest bidder gets Mona Lisa
    require (msg.sender != highestBidder);
    // return bid to bidder
    uint amount = pendingReturns[msg.sender];
    msg.sender.send(amount)
}
```

Spot the Bug!


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function collect() public {
  // highest bidder gets Mona Lisa
  require (msg.sender != highestBidder);
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Hint: function can be called at *any time* by a bidder

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Protocol Violation!

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Asset is Duplicated!

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What is the Transaction Fee?


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Need Automatic Execution Cost Prediction!

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The Nomos Language

Smart Contracts

Resource-Aware Session Types

Challenges:

1. *contract protocols are violated*
2. *asset duplication/deletion*
3. *automatic inference of execution cost*

Solutions:

1. *session types enforce protocols*
2. *linear types track assets*
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Protocol Enforcement with Types

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running phase

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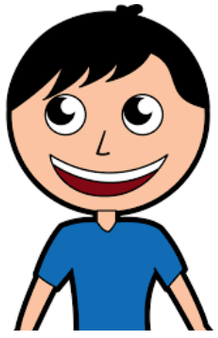
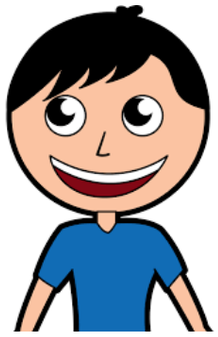


bid

Protocol Enforcement with Types

running phase



bid

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compilation error

Protocol Enforcement with Types

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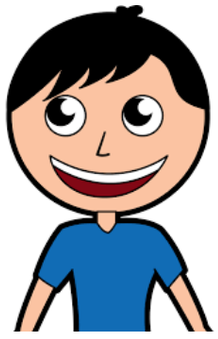

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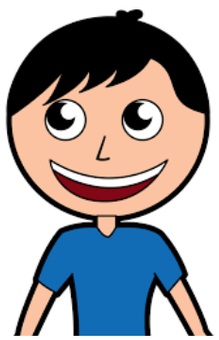

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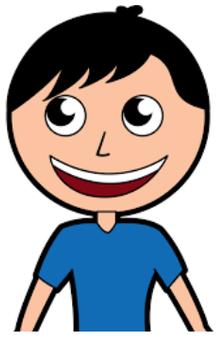

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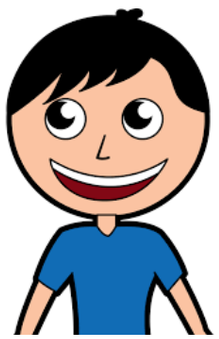

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Protocol Enforcement with Types

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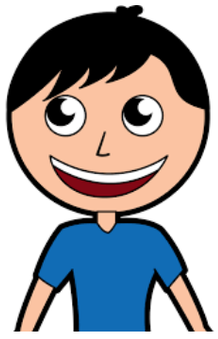

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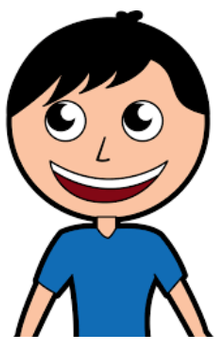

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Auction as a Session Type

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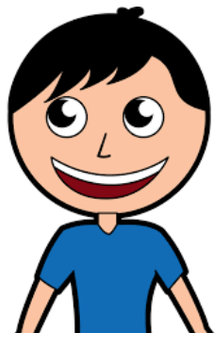

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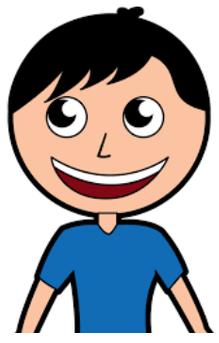

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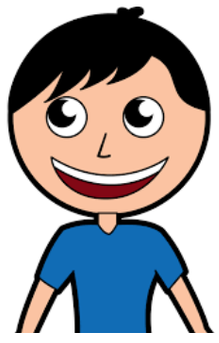

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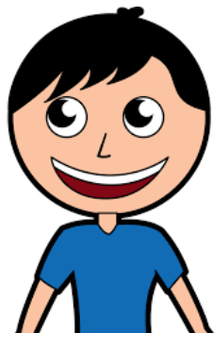

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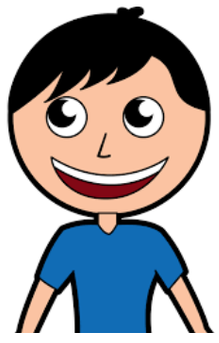

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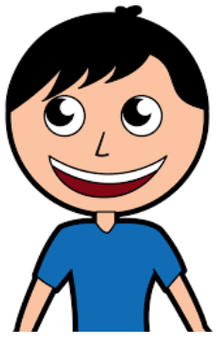

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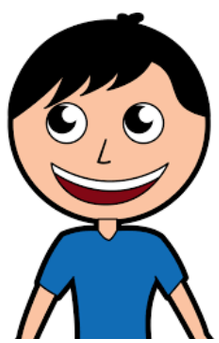

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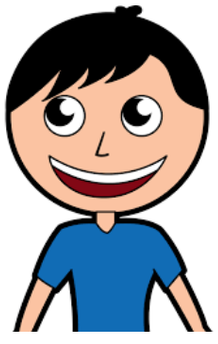

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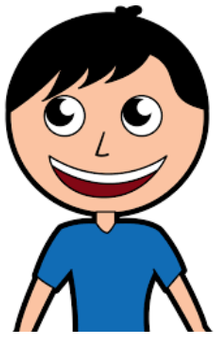

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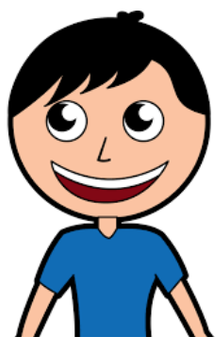

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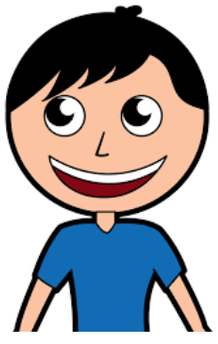

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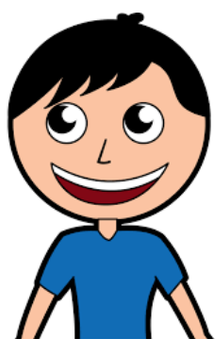

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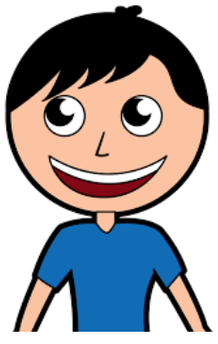

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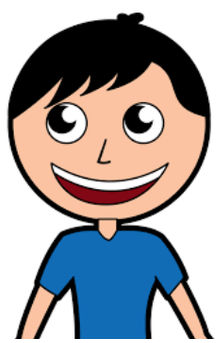

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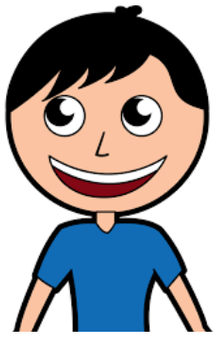

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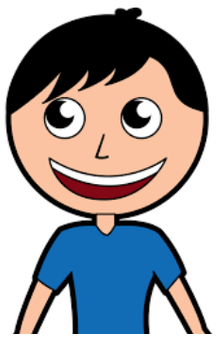

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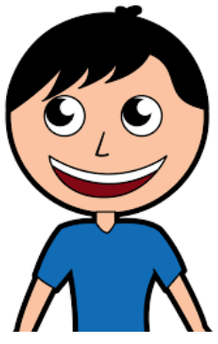

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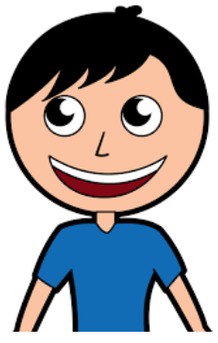

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Get Asset Preservation for Free!

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$$\begin{aligned} \mathit{type}\ \mathsf{auction} = {} & \triangleleft^{3} \oplus \{\mathbf{running} : \&\{\mathbf{bid} : \mathsf{money} \multimap \triangleright^{1}\mathsf{auction}\}, \\ & \mathbf{ended} : \&\{\mathbf{collect} : \oplus\{\mathbf{won} : \mathsf{monalisa} \otimes \triangleright^{0}\mathsf{auction}, \\ & \qquad \mathbf{lost} : \mathsf{money} \otimes \triangleright^{0}\mathsf{auction}\}\}\} \end{aligned}$$

Expressing Transaction Fee

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user pays 3 units as fees at start of execution

return leftover fee back to user in the end

Cost Computation is Automatic!

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$$\mathit{type}\ \mathsf{auction} = \triangleleft^* \oplus \{\mathbf{running} : \&\{\mathbf{bid} : \mathsf{money} \multimap \triangleright^* \mathsf{auction}\},$$
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Linear constraints shipped to LP solver

Constraints are solved and substituted back into the program

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How do you compute the execution cost of distributed computation?

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Cost may depend on number of processes, buffer sizes, etc.

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Inter-process dependencies

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How do you compute the execution cost of distributed computation?

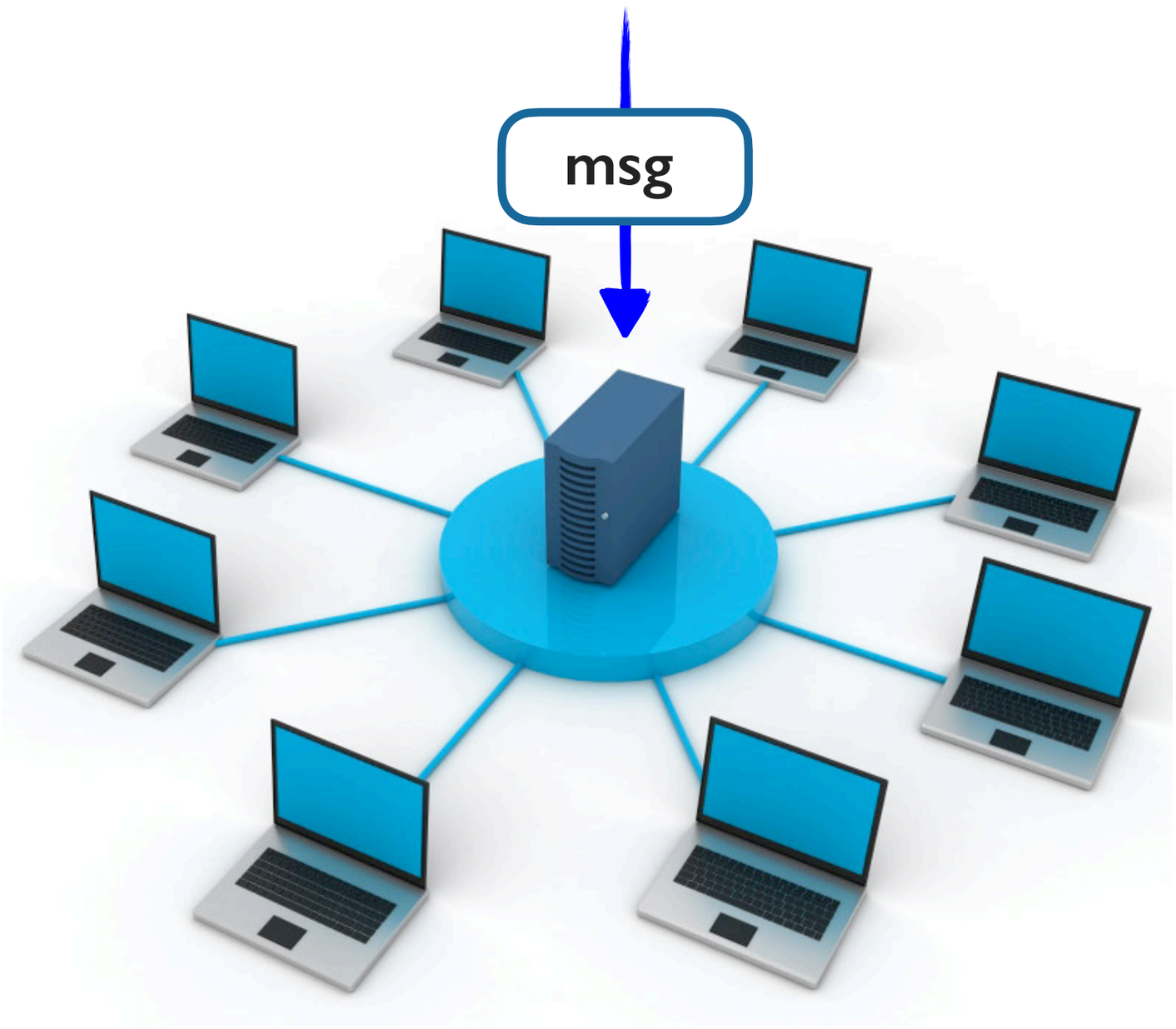
What should cost be function of?

No static data structures

Cost may depend on number of processes, buffer sizes, etc.

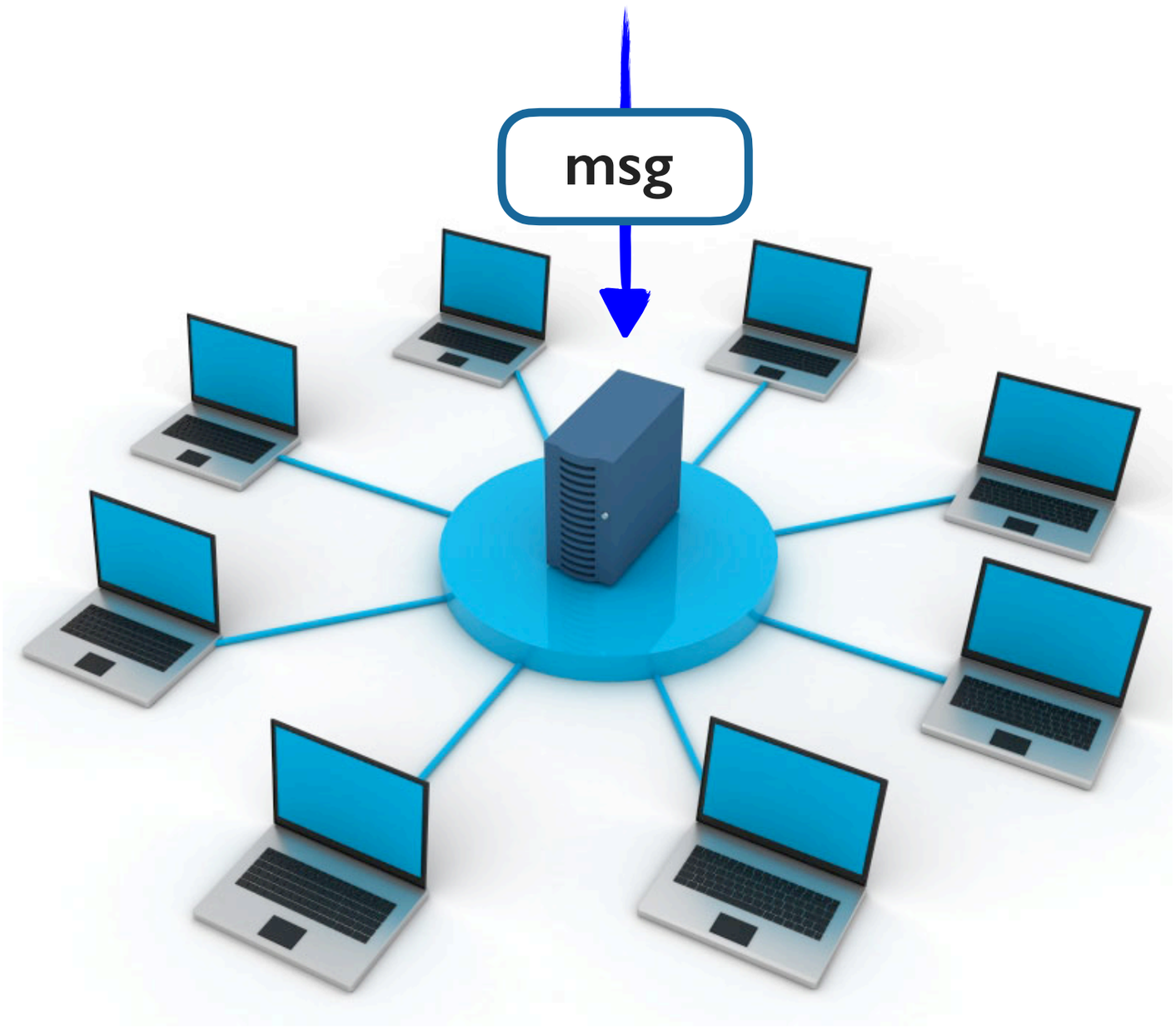
Inter-process dependencies

Resource-Aware Session Types



Resource-Aware Session Types

<u>Key Idea:</u> Messages carry potential & processes consume potential



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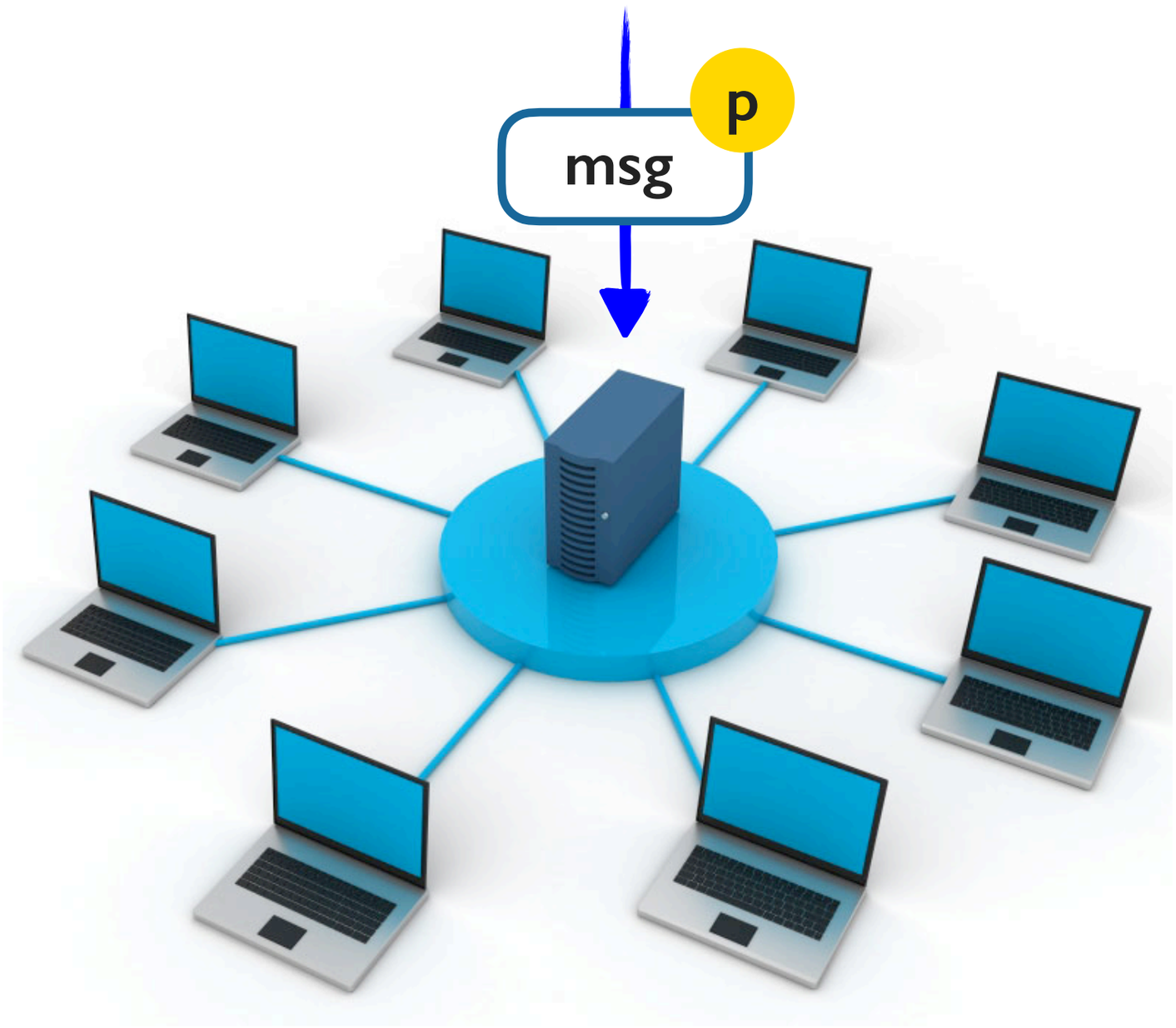

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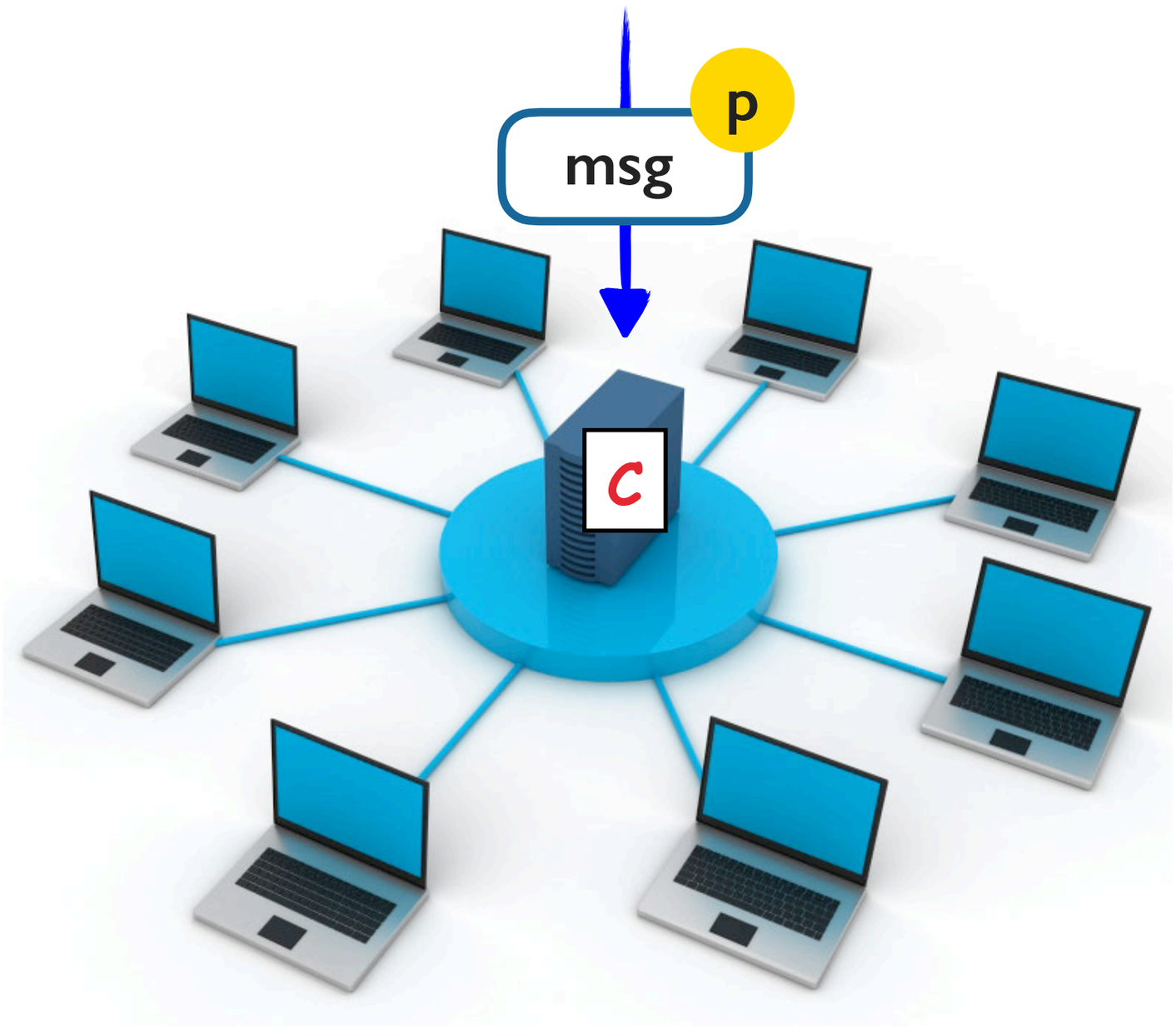

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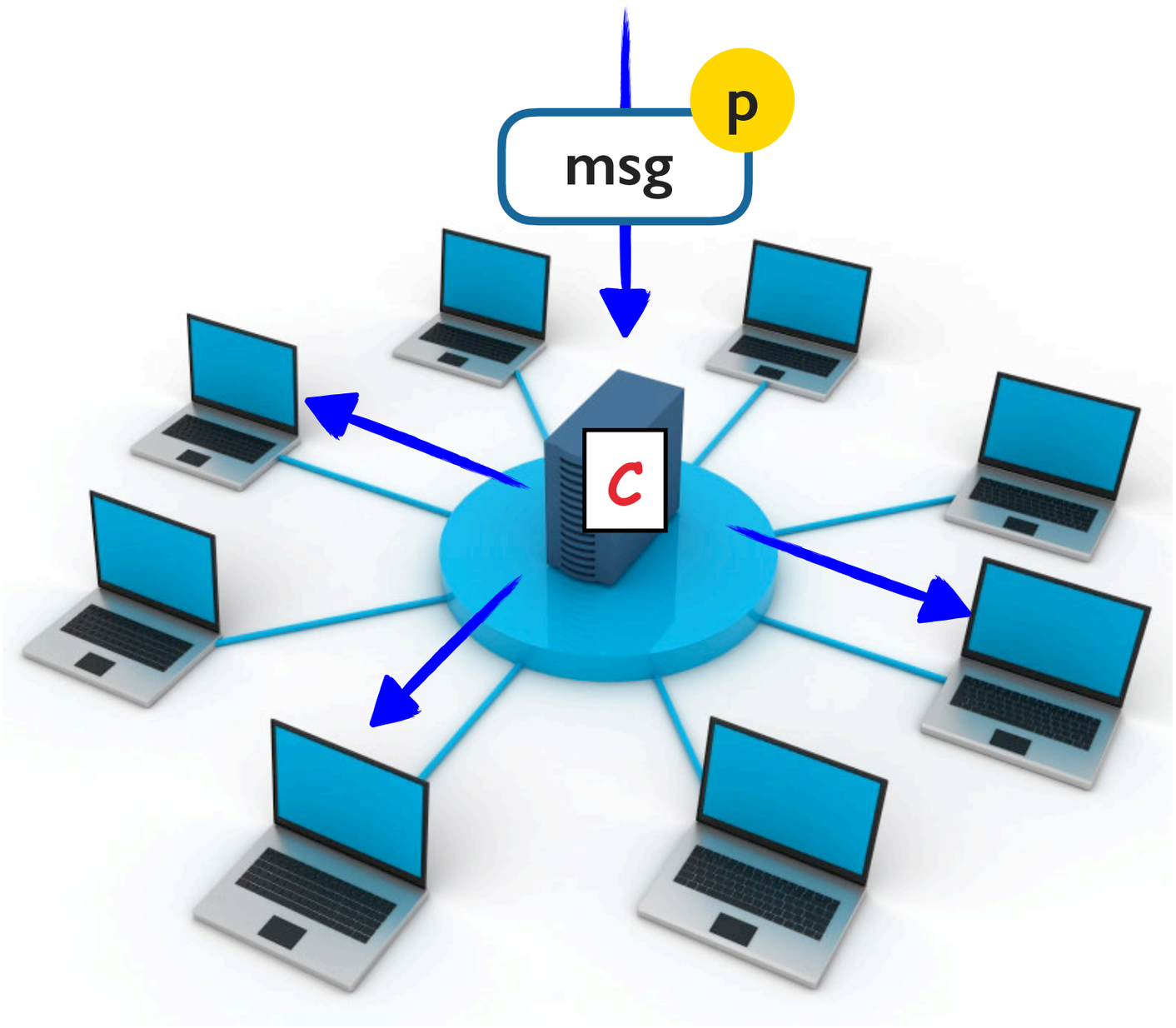

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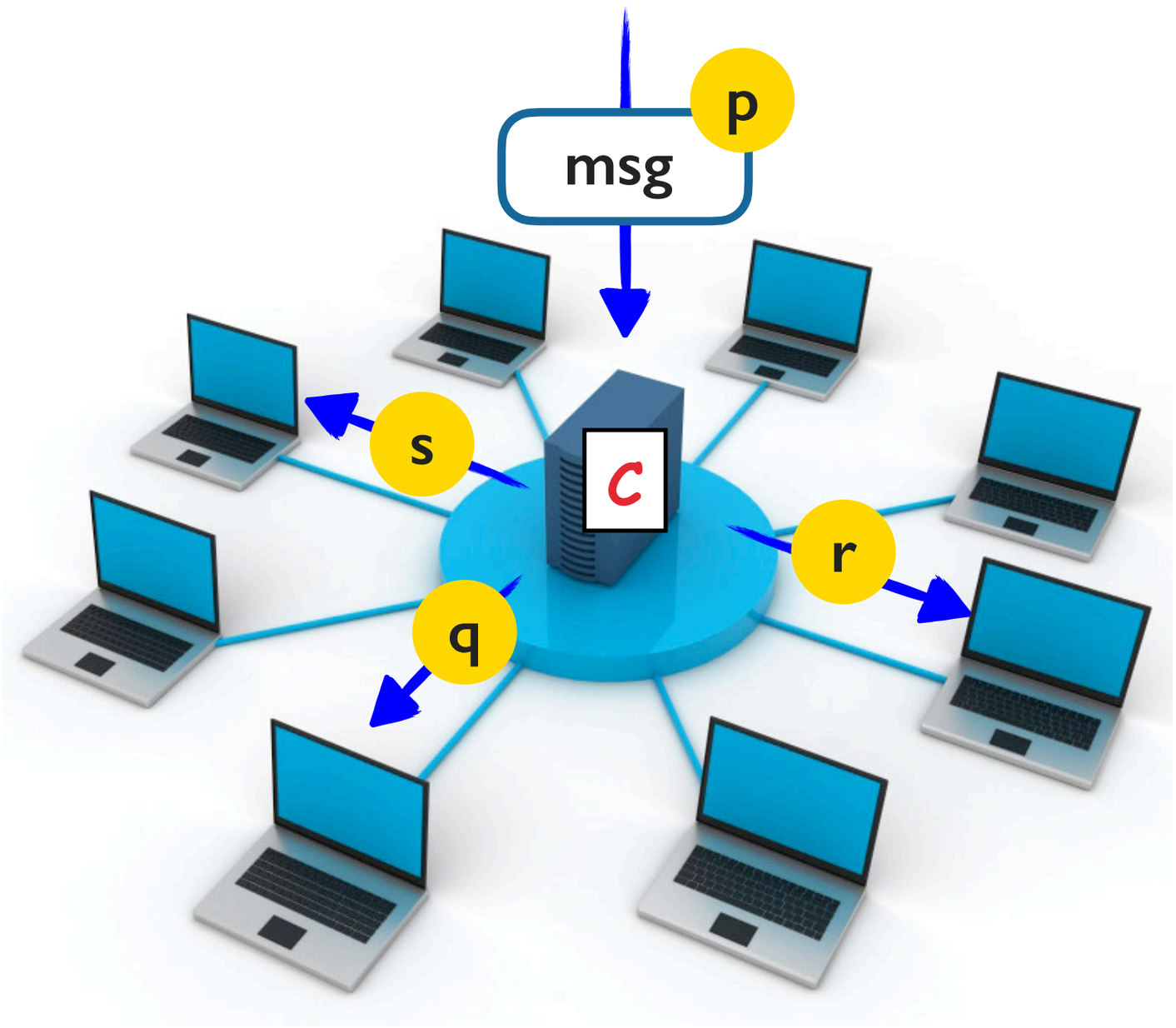

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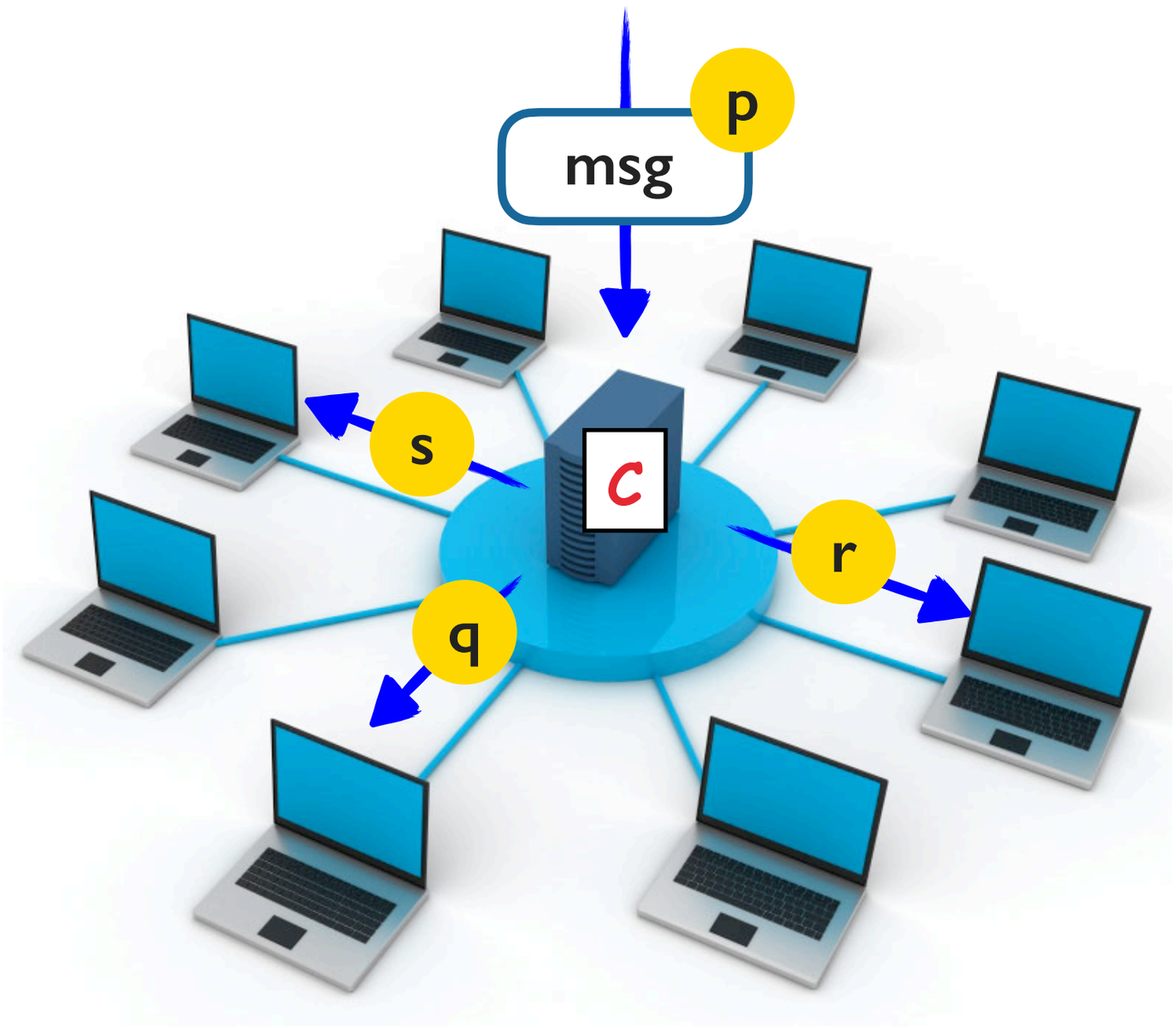

$$p = q + r + s + C$$

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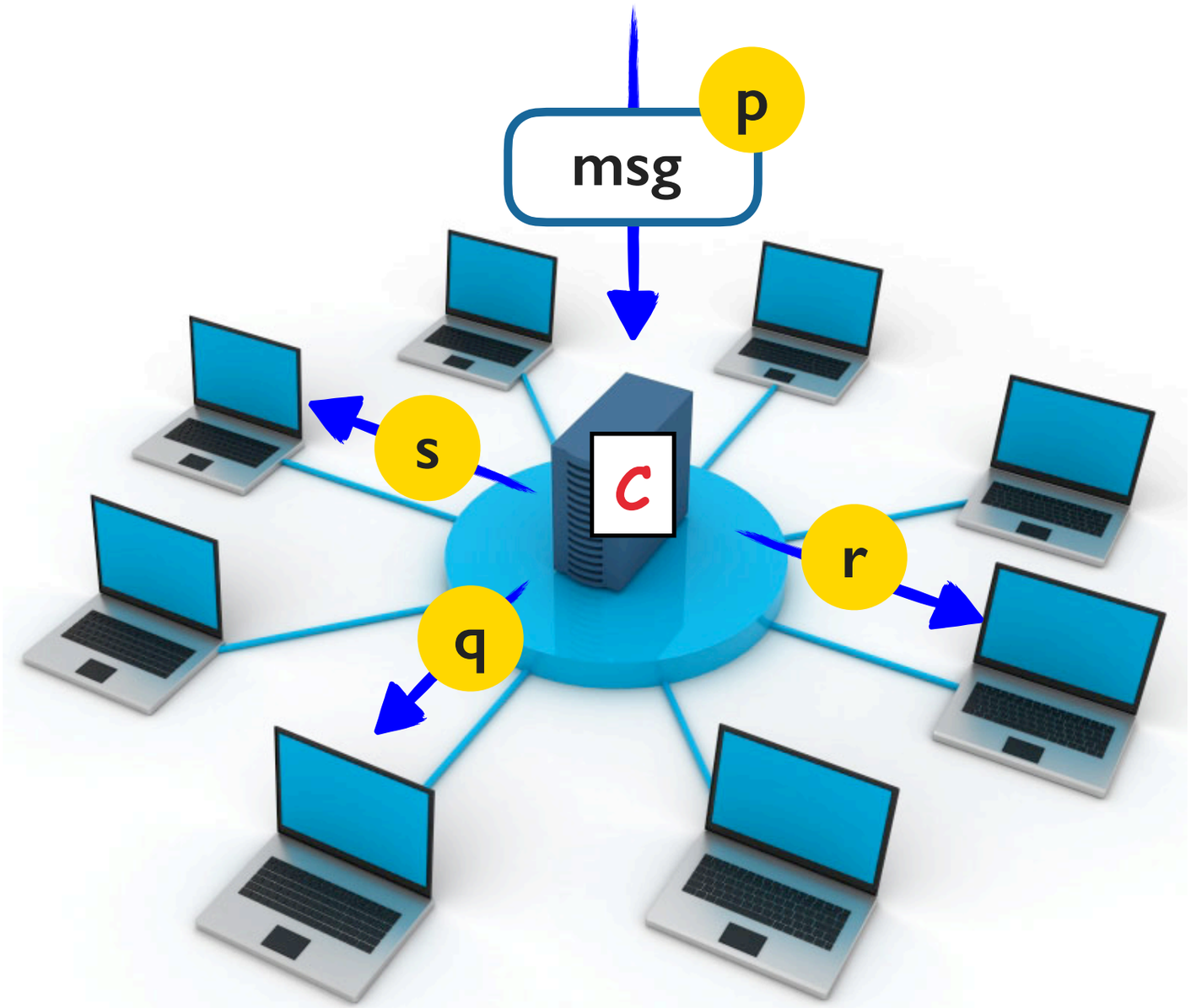

$$p = q + r + s + C$$

$$p, q, r, s \geq 0$$

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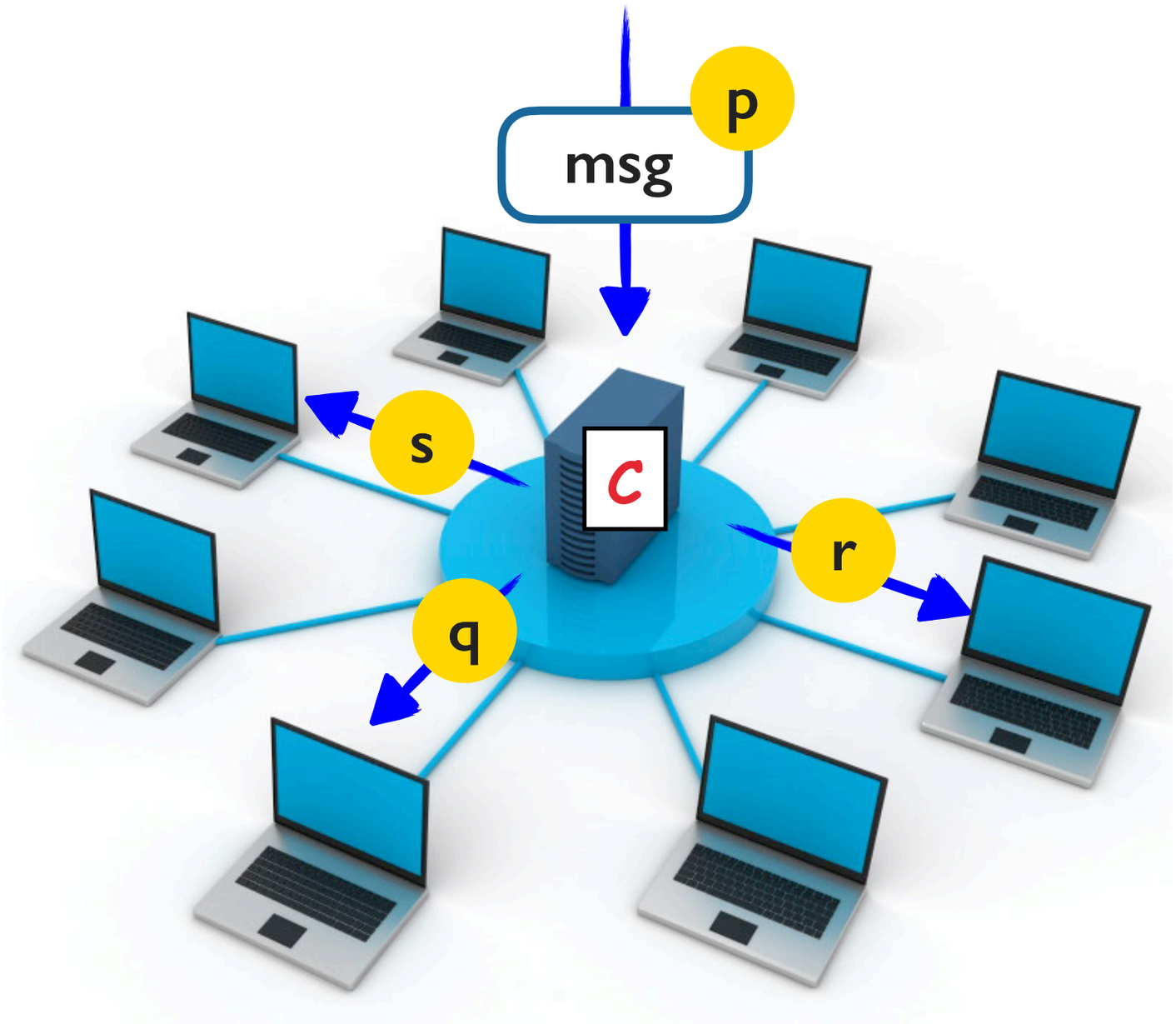

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$$\bullet \quad \bullet \quad \bullet$$

Talk Outline

Protocol Enforcement & Asset Preservation

Probabilistic Reasoning

Performance & Verification

Nomos

Resource-Aware Session Types

[LICS '18, SAS '20, CSF '21]

NomosPro

Probabilistic Session Types

[POPL '23]

Rast

Refinement Session Types

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Session Types

Type system for concurrent message-passing programs

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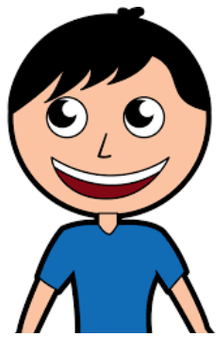
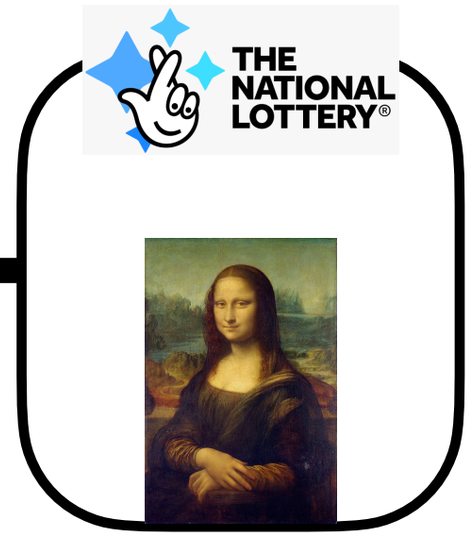
Probabilistic Smart Contracts





Probabilistic Smart Contracts

$$\textit{type}\ \text{lottery} = \oplus\{\mathbf{running} : \&\{\mathbf{buy} : \text{money} \multimap \text{lottery}\},$$
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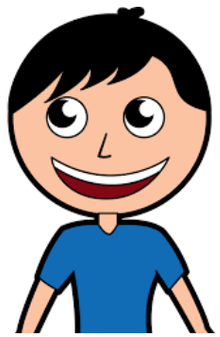

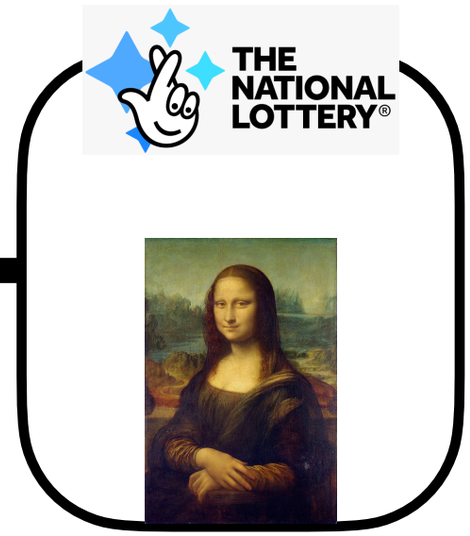

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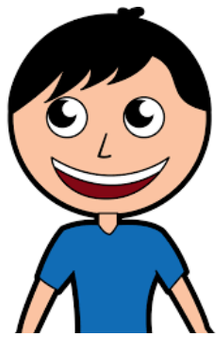

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Session Type Does Not Capture Probabilistic Behavior

What if 'won' is sent to nobody?

Probabilistic Session Types

Probabilistic Session Types

<u>Key Idea:</u> NomosPro enhance session types with probabilities to capture prob. distribution of messages

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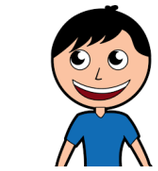

lost

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lost

✗ *compilation error*

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How to Track Probabilities?

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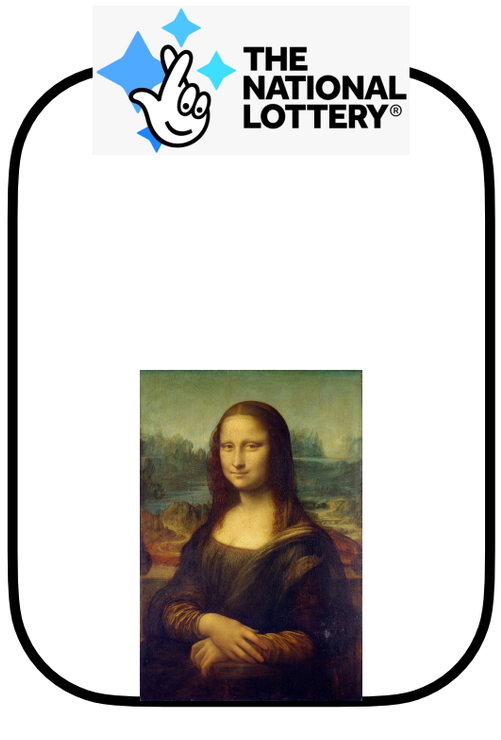

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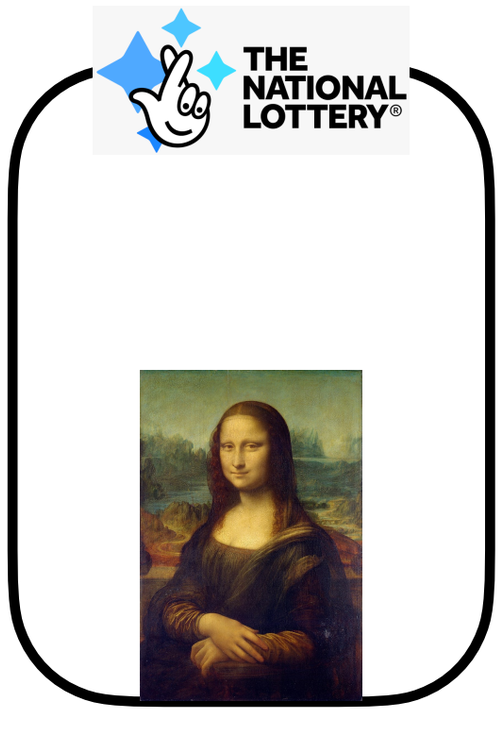

won [prob. = 0]
lost [prob. = 1]

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✓ *compilation successful*

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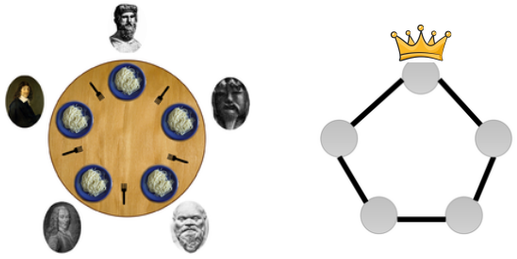
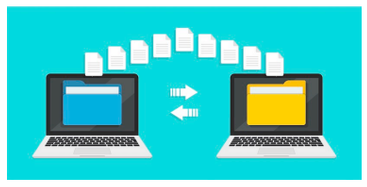
Applications of NomosPro

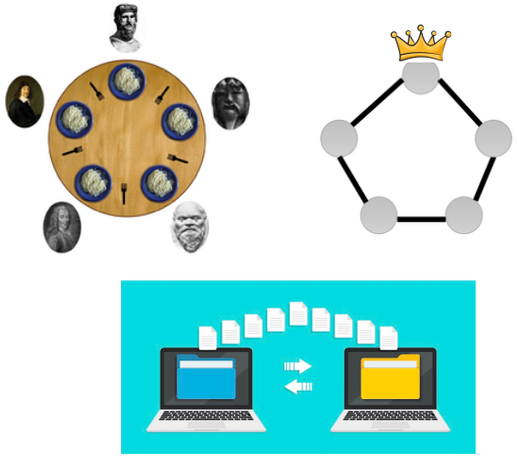
Applications of NomosPro



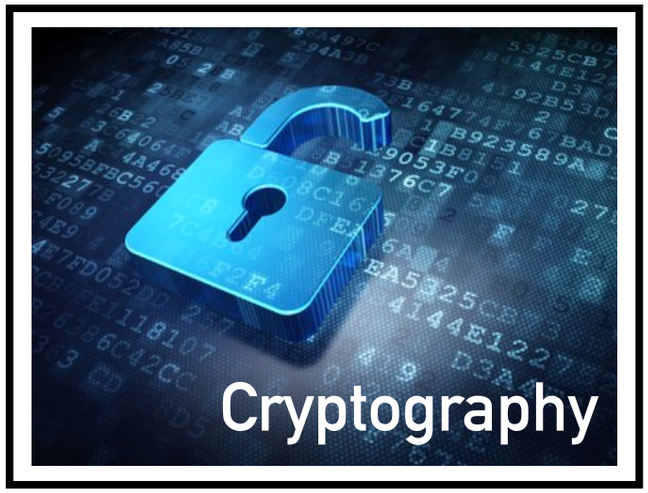


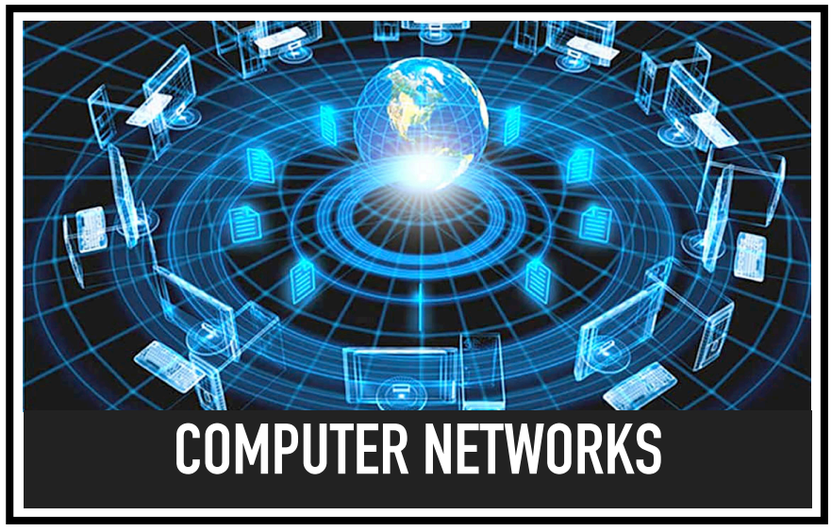
Randomized Algorithms

Applications of NomosPro

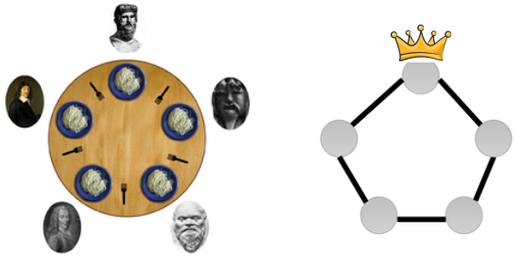


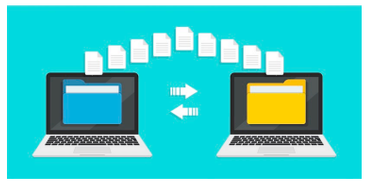
Randomized Algorithms



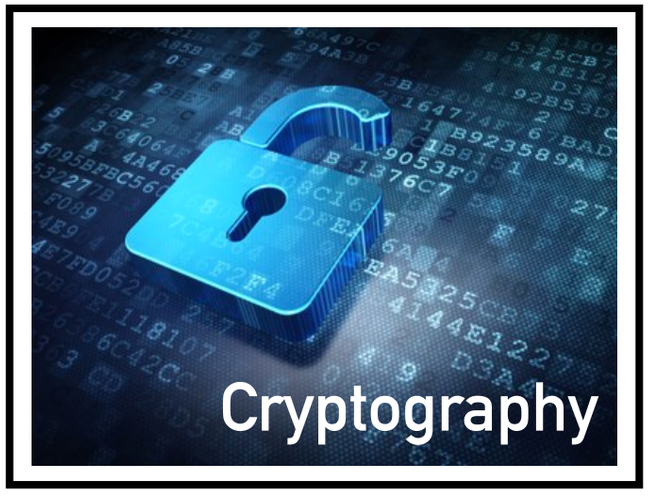


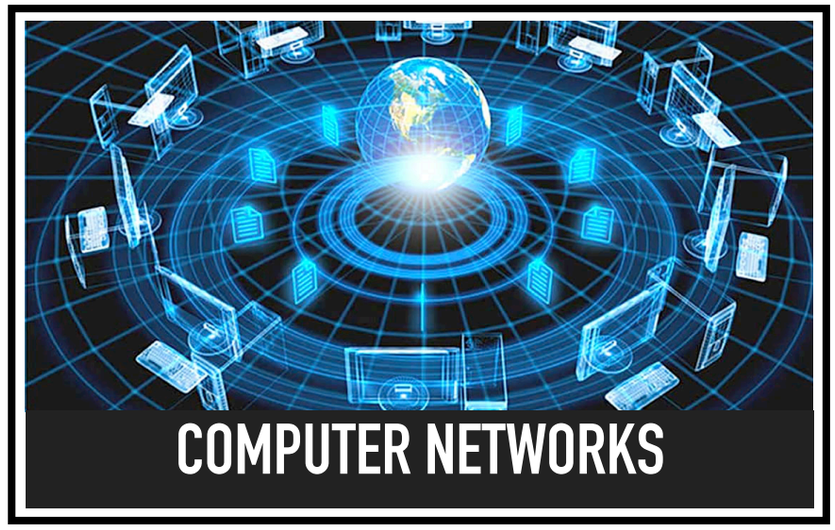
Applications of NomosPro

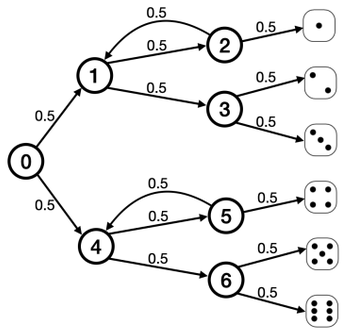


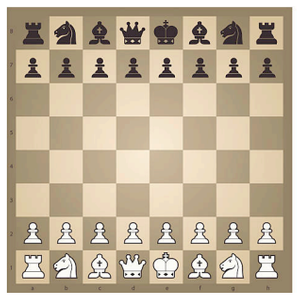


Randomized Algorithms

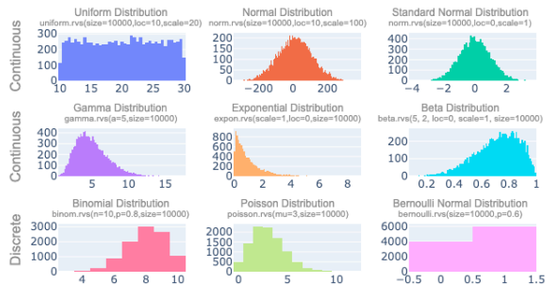






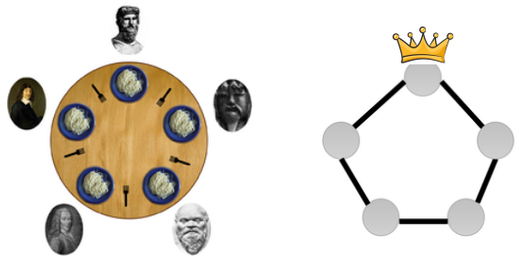


Markov Chains

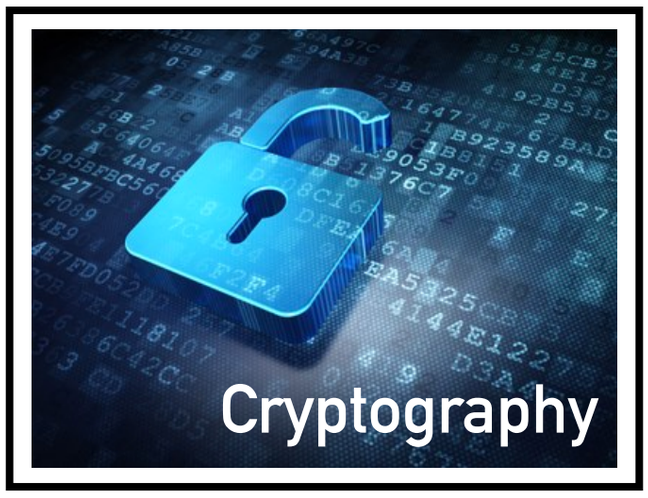


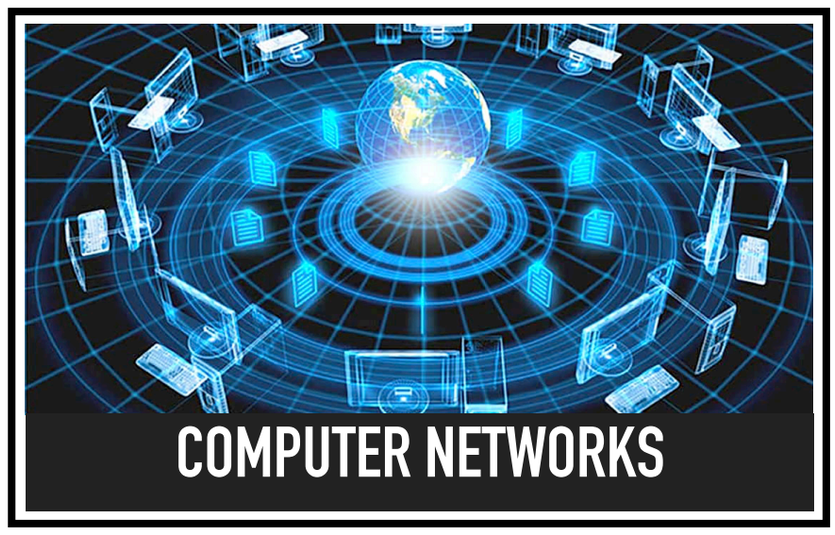
Modeling Unknown Distributions

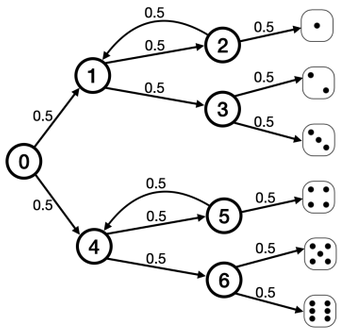
Applications of NomosPro

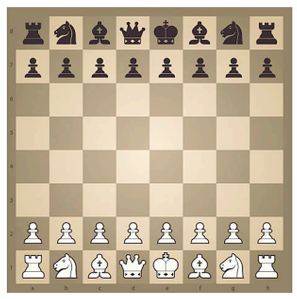


Randomized Algorithms









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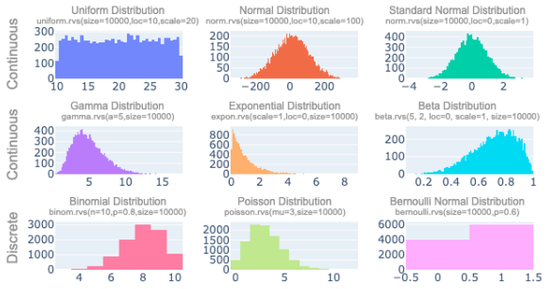


Modeling Unknown Distributions

Talk Outline

Protocol Enforcement & Asset Preservation

Probabilistic Reasoning

Performance & Verification

Nomos

Resource-Aware Session Types

[LICS '18, SAS '20, CSF '21]

NomosPro

Probabilistic Session Types

[POPL '23]

Rast

Refinement Session Types

[ICFP '18, FSCD '20, CONCUR '20]

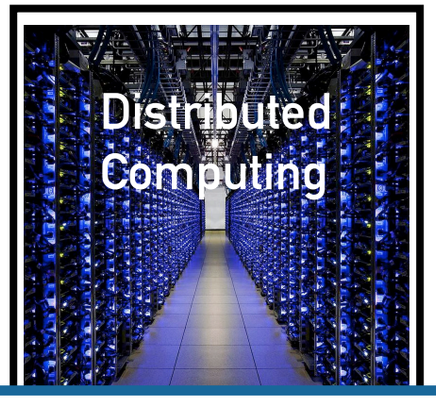
Session Types

Type system for concurrent message-passing programs

Talk Outline

Protocol Enforcement & Asset Preservation

Probabilistic Reasoning



Performance & Verification

Nomos

Resource-Aware Session Types

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Probabilistic Session Types

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Rast

Refinement Session Types

[ICFP '18, FSCD '20, CONCUR '20]

Session Types

Type system for concurrent message-passing programs

Who Wins the Auction?


```
function bid() public payable {
    uint bid = msg.value;
    address bidder = msg.sender;
    pendingReturns[bidder] = bid;
    if (bid > highestBid) {
        highestBidder = bidder;
        highestBid = bid;
    }
}
```

$$\begin{aligned} \mathit{type}\ \text{auction} = \oplus\{\mathbf{running} : \&\{\mathbf{bid} : \text{money} \multimap \text{auction}\}, \\ \mathbf{ended} : \&\{\mathbf{collect} : \oplus\{\mathbf{won} : \text{monalisa} \otimes \text{auction}, \\ \mathbf{lost} : \text{money} \otimes \text{auction}\}\}\} \end{aligned}$$

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```

What if bid < highestBid*?*

$$\mathit{type}\ \text{auction} = \oplus\{\mathbf{running} : \&\{\mathbf{bid} : \text{money} \multimap \text{auction}\},$$
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```


What if bid < highestBid?

Session Type Does Not Encode Logical Constraints

$$type\ \text{auction} = \oplus\{\mathbf{running} : \&\{\mathbf{bid} : \text{money} \multimap \text{auction}\},$$
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$$\mathbf{lost} : \text{money} \otimes \text{auction}\}\}\}$$

Tracking Highest Bid in Type

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<u>Key Idea:</u> Session types in Rast are indexed with integers capturing arithmetic properties

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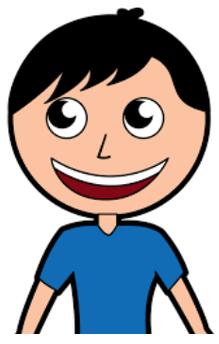
$$\textit{type}\ \text{auction}[\textit{max}] = \oplus\{\textbf{running} : \&\{\textbf{bid} : \text{money}[m \mid m > \textit{max}] \multimap \text{auction}[m]\},$$
$$\textbf{ended} : \&\{\textbf{collect} : \oplus\{\textbf{won} : \text{monalisa} \otimes \text{auction}[\textit{max}],$$
$$\textbf{lost} : \text{money}[m \mid m < \textit{max}] \otimes \text{auction}[\textit{max}]\}\}\}$$

Tracking Highest Bid in Type

running phase



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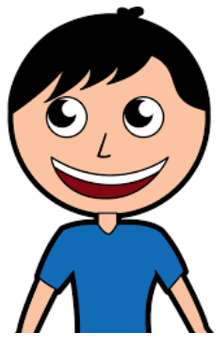
Tracking Highest Bid in Type

running phase



[*max*]

$$\mathit{type}\ \text{auction}[\mathit{max}] = \oplus\{\textbf{running} : \&\{\textbf{bid} : \text{money}[m \mid m > \mathit{max}] \multimap \text{auction}[m]\},$$
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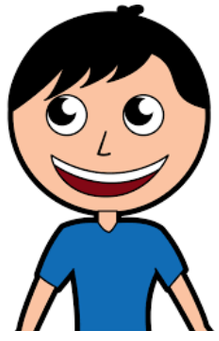
Tracking Highest Bid in Type

running phase



money $[m \mid m > max]$

$[max]$

$$type\ \text{auction}[max] = \oplus\{\textbf{running} : \&\{\textbf{bid} : \text{money}[m \mid m > max] \multimap \text{auction}[m]\},$$
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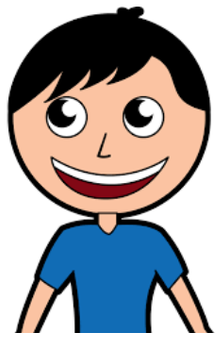
Tracking Highest Bid in Type

running phase



[*max*]

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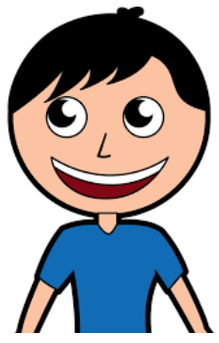
Tracking Highest Bid in Type

running phase



~~[*max*]~~

[*m*]

$$\textit{type}\ \text{auction}[max] = \oplus\{\textbf{running} : \&\{\textbf{bid} : \text{money}[m \mid m > max] \multimap \text{auction}[m]\},$$
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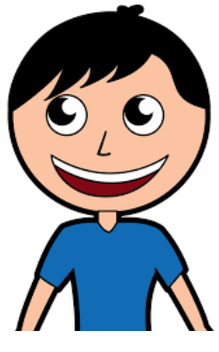
Tracking Highest Bid in Type

running phase



~~[*max*]~~

[*m*]

ended phase

[*max*]

$$\textit{type}\ \text{auction}[\textit{max}] = \oplus\{\textbf{running} : \&\{\textbf{bid} : \text{money}[m \mid m > \textit{max}] \multimap \text{auction}[m]\},$$
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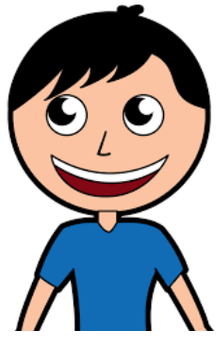
Tracking Highest Bid in Type

running phase



~~[*max*]~~

[*m*]

ended phase

money [*m* | *m* < *max*]

[*max*]

$$\textit{type}\ \text{auction}[\textit{max}] = \oplus\{\textbf{running} : \&\{\textbf{bid} : \text{money}[m \mid m > \textit{max}] \multimap \text{auction}[m]\},$$
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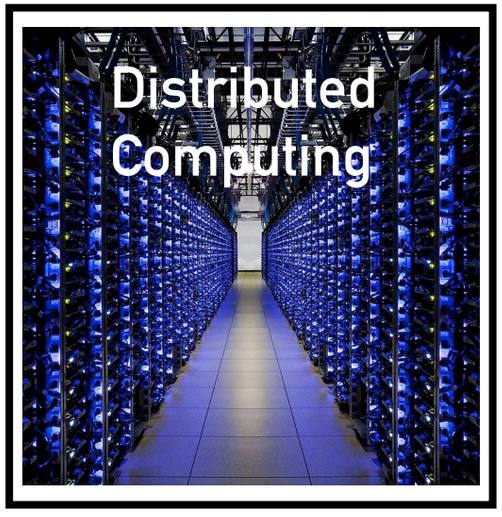
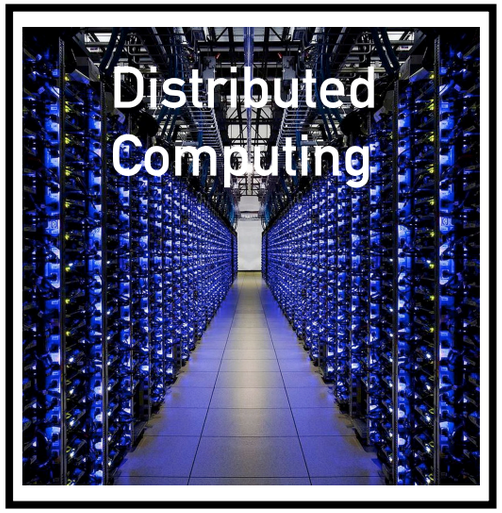
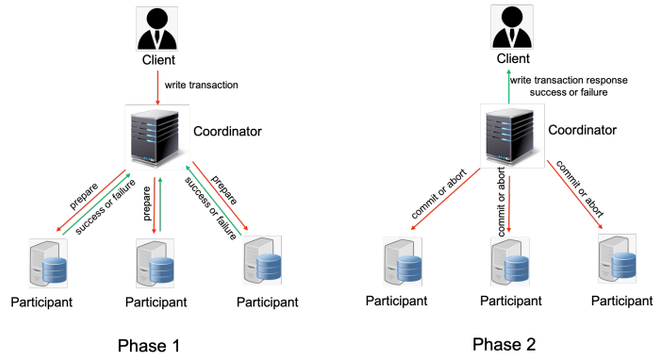
Applications of Rast

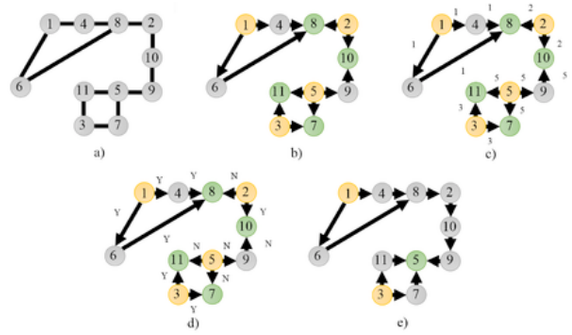
Applications of Rast



Applications of Rast

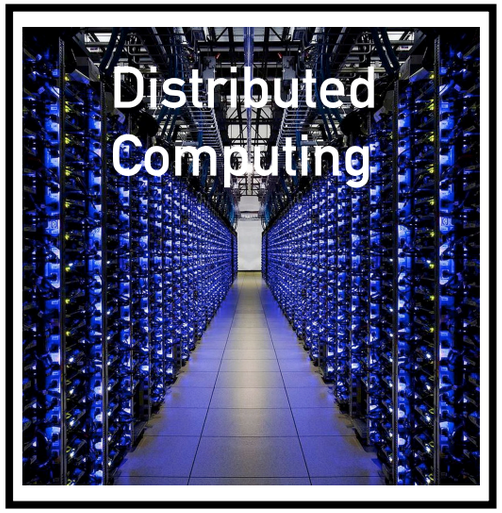


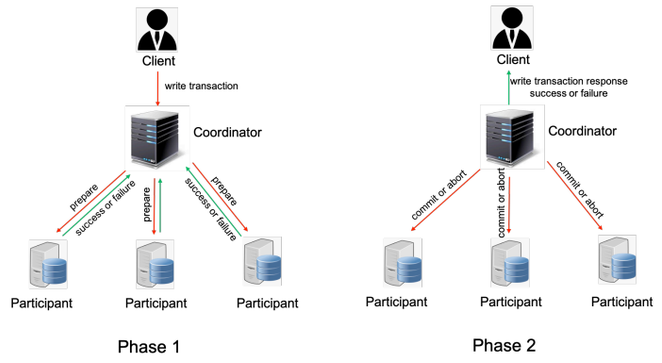


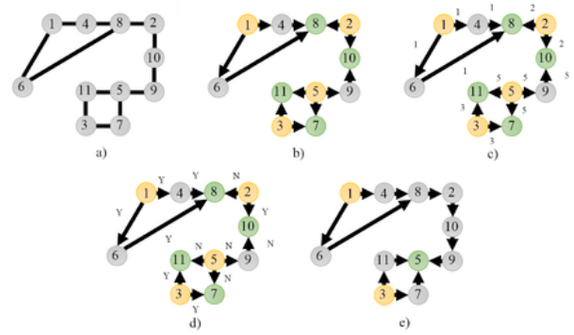


Lightweight Verification of Distributed Algorithms

Applications of Rast







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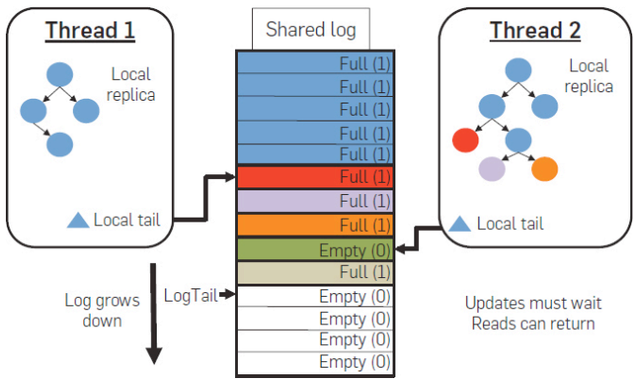
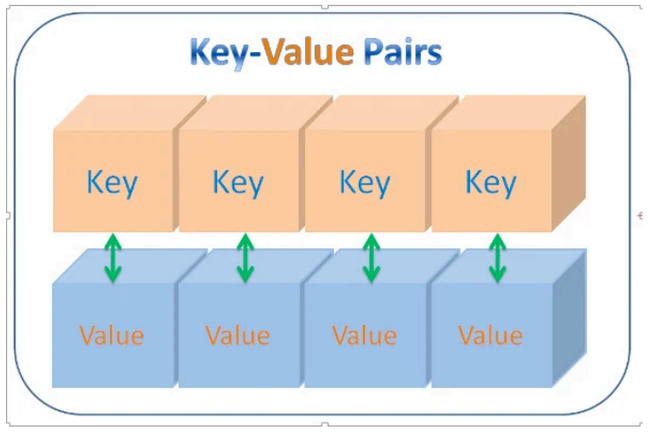
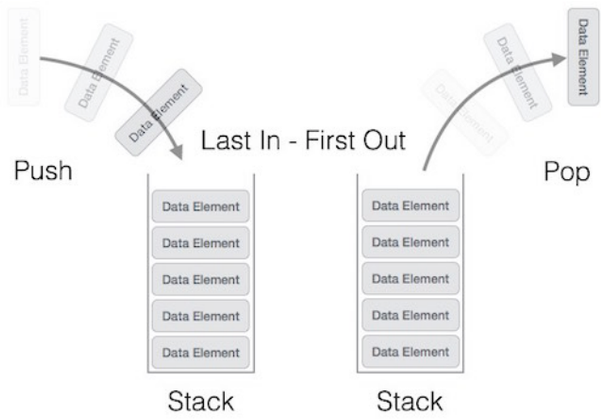




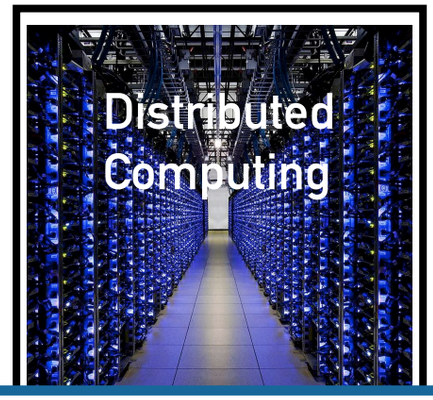


Analysis of Concurrent Data Structures

Key Takeaways

Protocol Enforcement & Asset Preservation

Probabilistic Reasoning



Performance & Verification

Nomos

Resource-Aware Session Types

[LICS '18, SAS '20, CSF '21]

NomosPro

Probabilistic Session Types

[POPL '23]

Rast

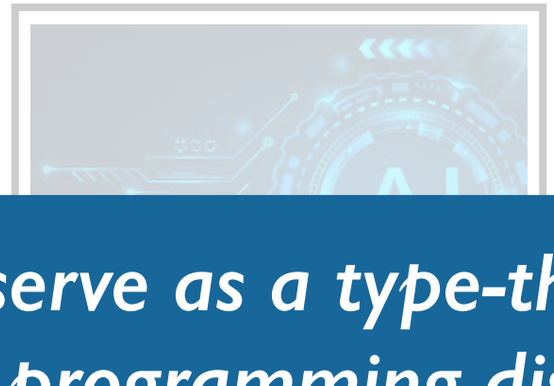
Refinement Session Types

[ICFP '18, FSCD '20, CONCUR '20]

Session Types

Type system for concurrent message-passing programs

Key Takeaways



- *Session Types serve as a type-theoretic foundation for programming distributed systems*
- *Domain-specific abstractions provide domain-specific guarantees*
- *Guarantees are provided by the type itself, which acts as a specification*
- *No need to analyze code once it has compiled!*

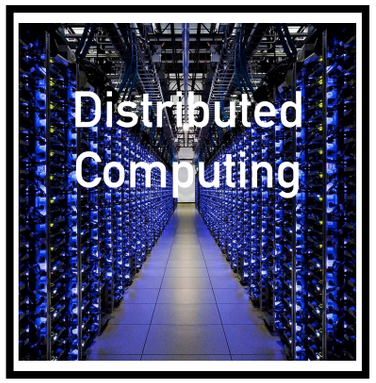
Session Types

Type system for concurrent message-passing programs

Future Research

Adapting PL Techniques to the Distributed Age

Future Research Directions



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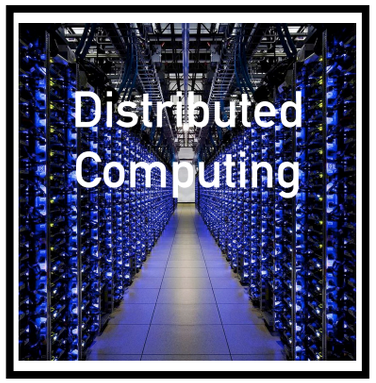

More Application Domains …

Nomos

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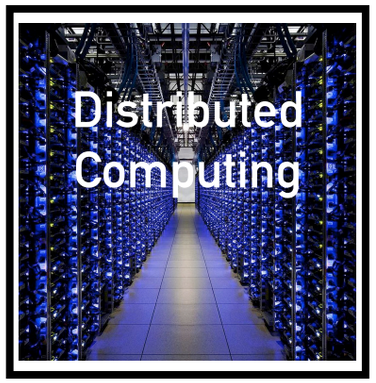

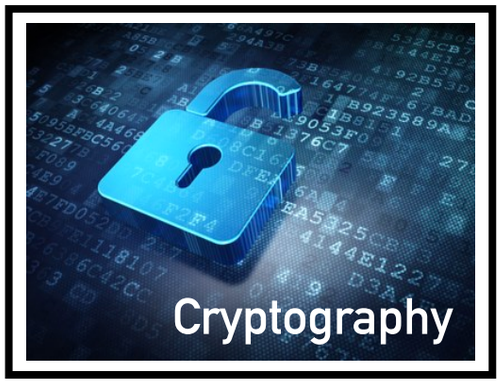

More Application Domains …

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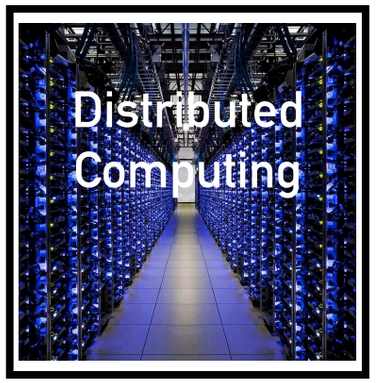
NomosUC

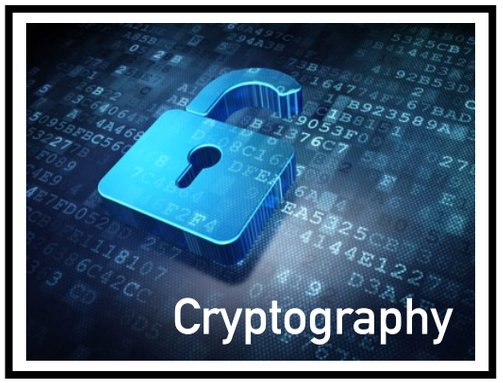
Import Session Types

Session Types

Type system for concurrent message-passing programs

Future Research Directions





More Application Domains …

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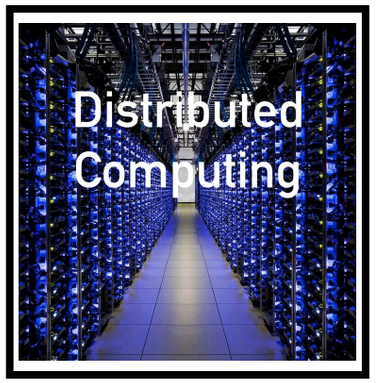
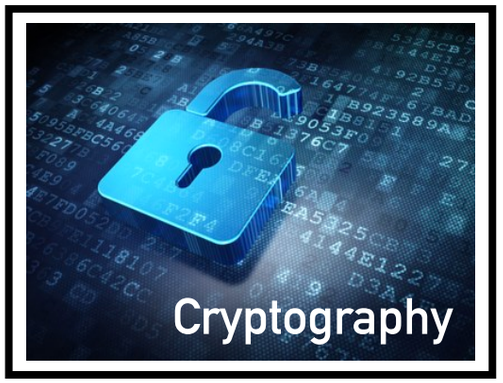
Session Types

Type system for concurrent message-passing programs

Dependent Session Types

Future Research Directions





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Type system for concurrent message-passing programs

Dependent Session Types

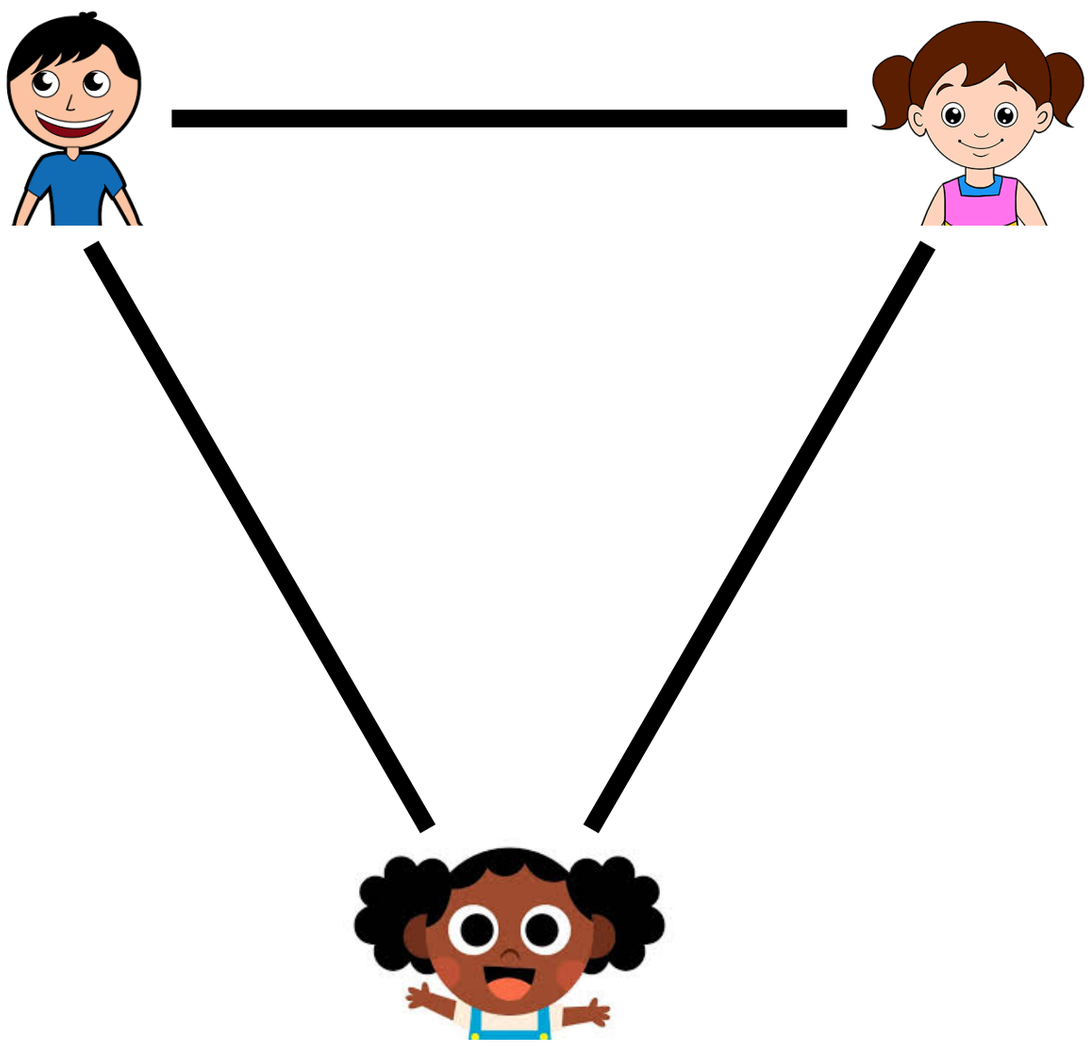
Encoding Failures, Timeouts

Cryptographic Protocols

SSL/TLS

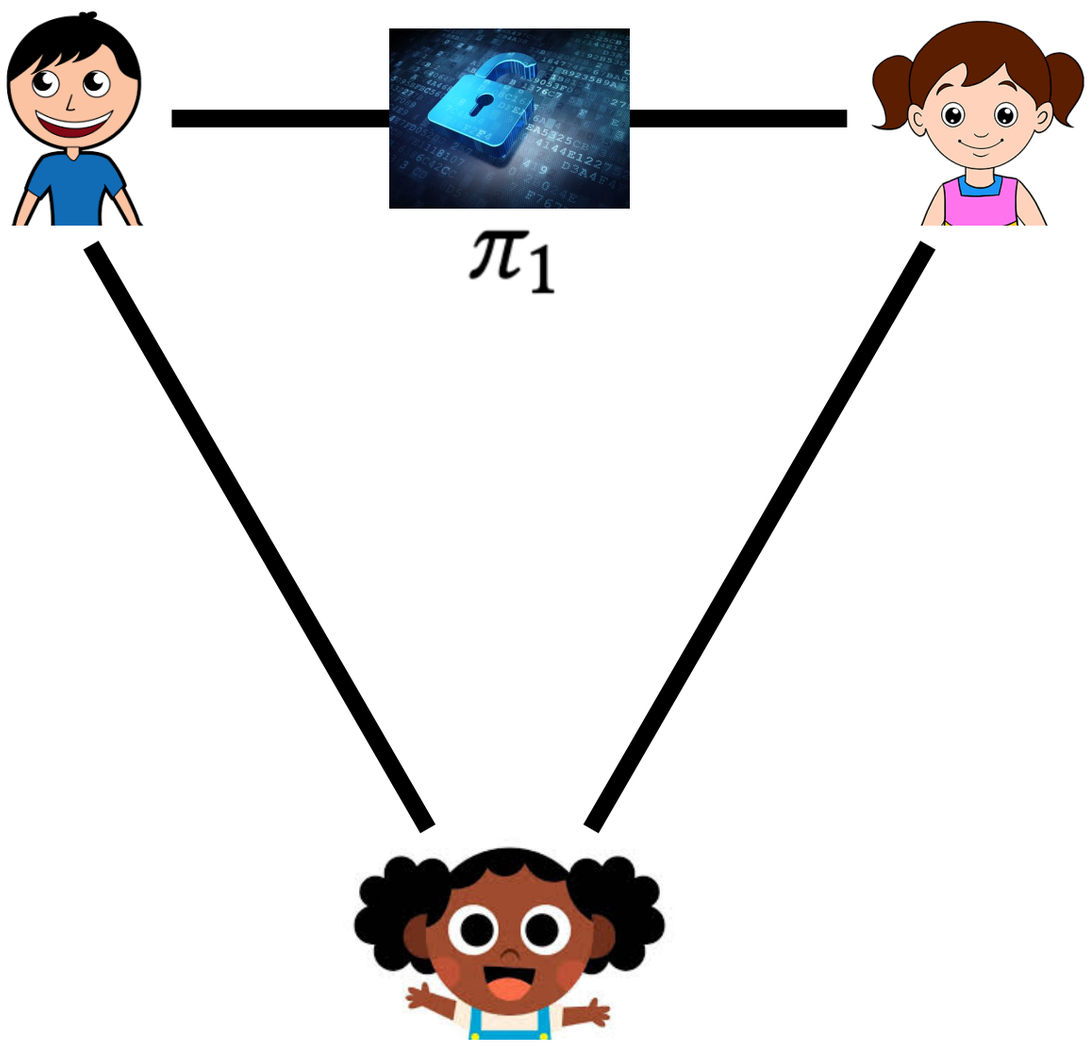
Cryptographic Protocols

SSL/TLS



Cryptographic Protocols

SSL/TLS



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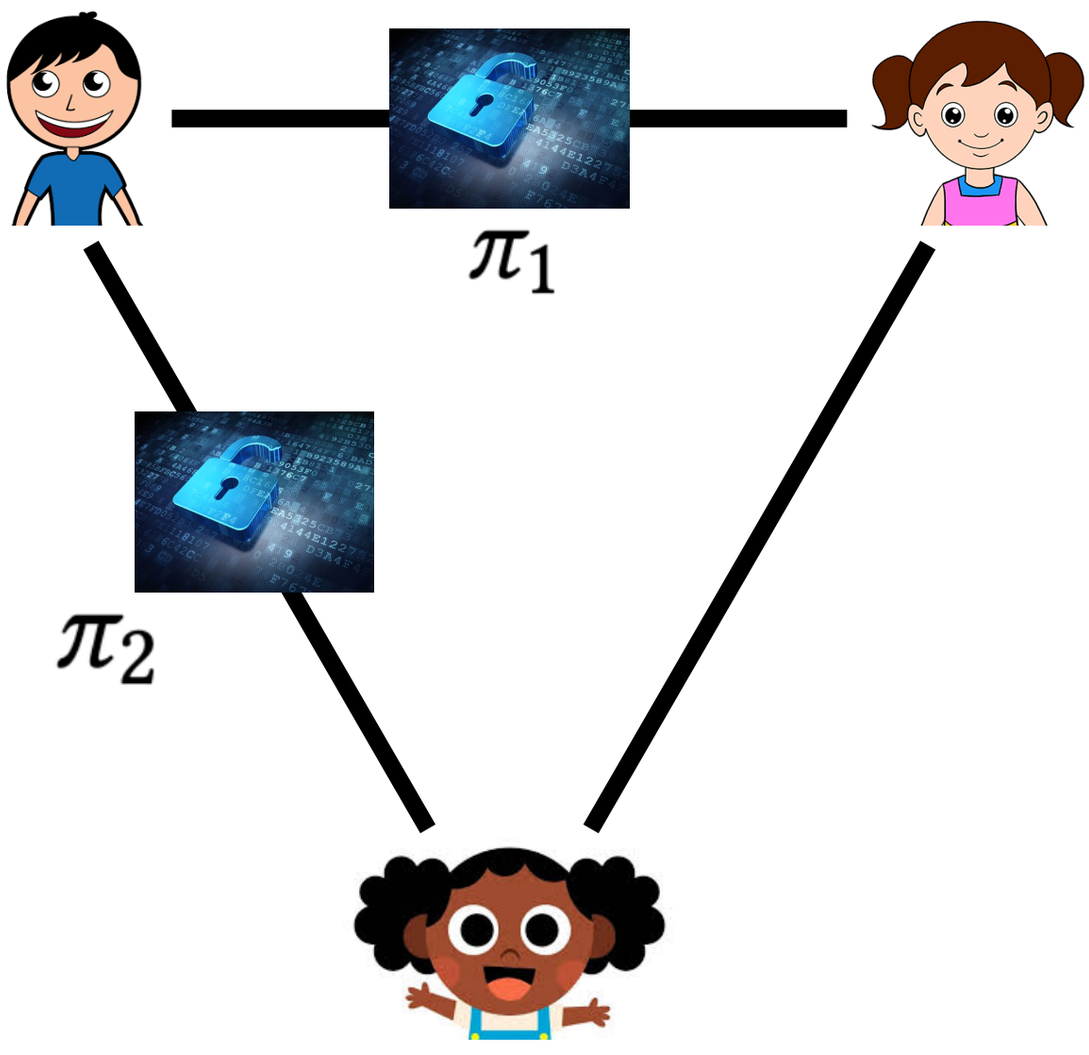

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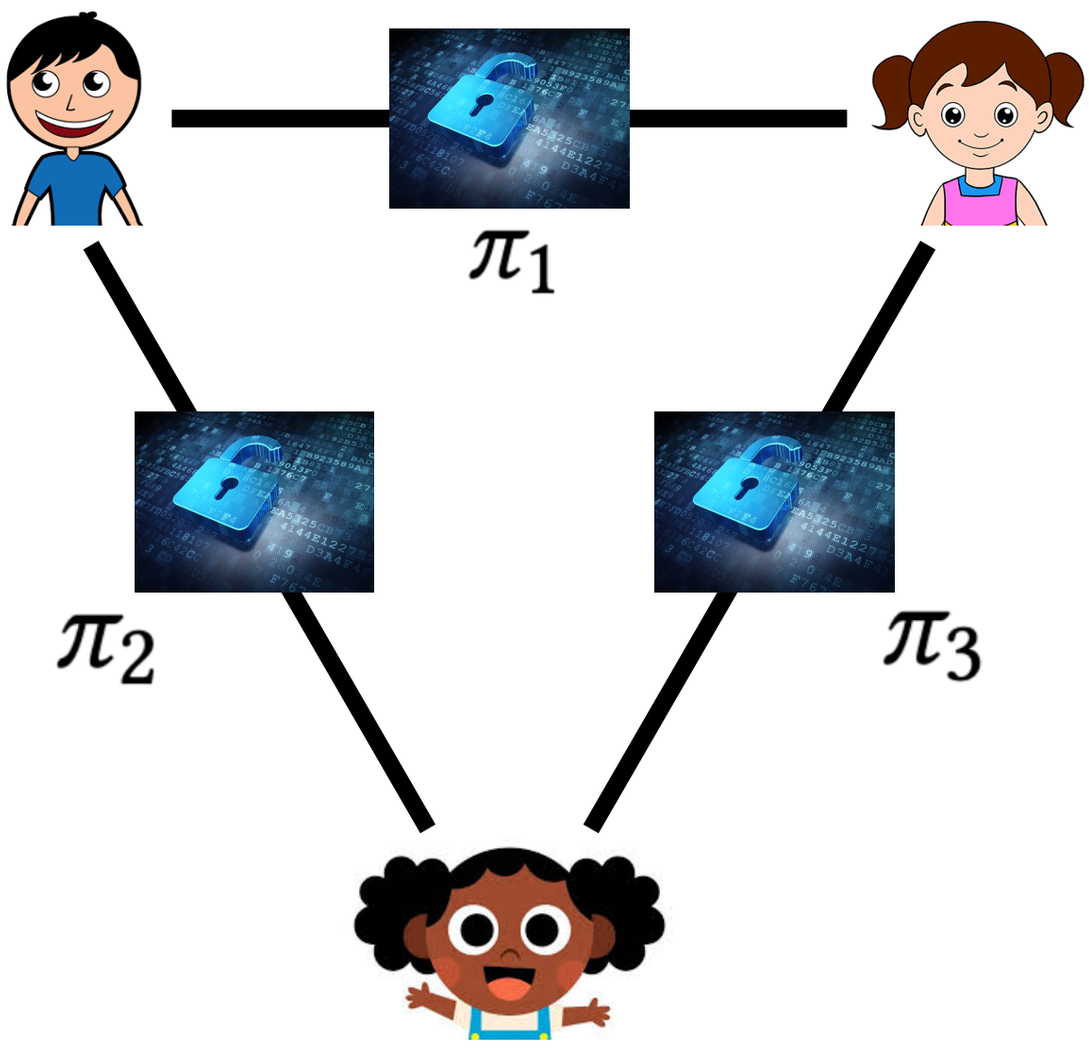

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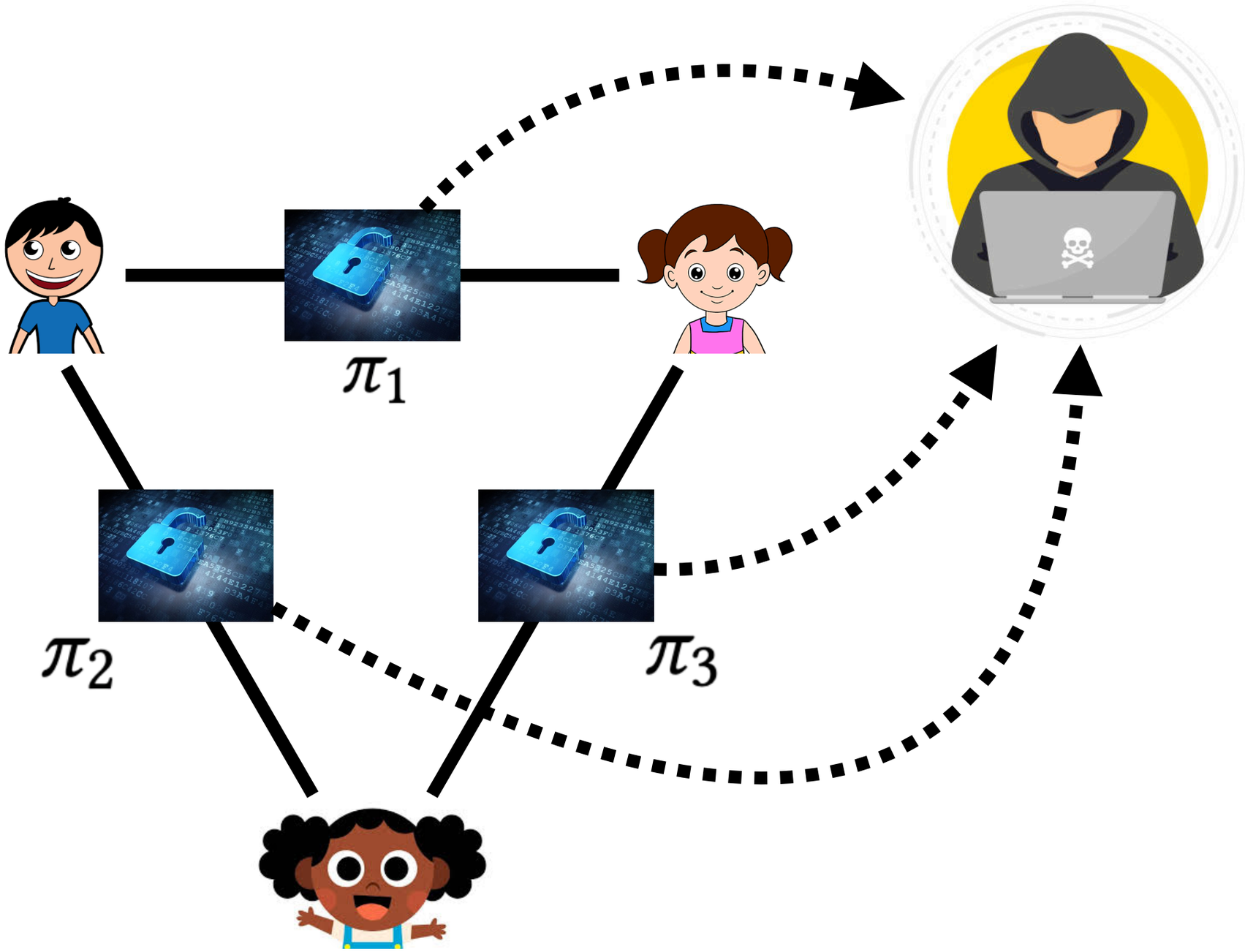
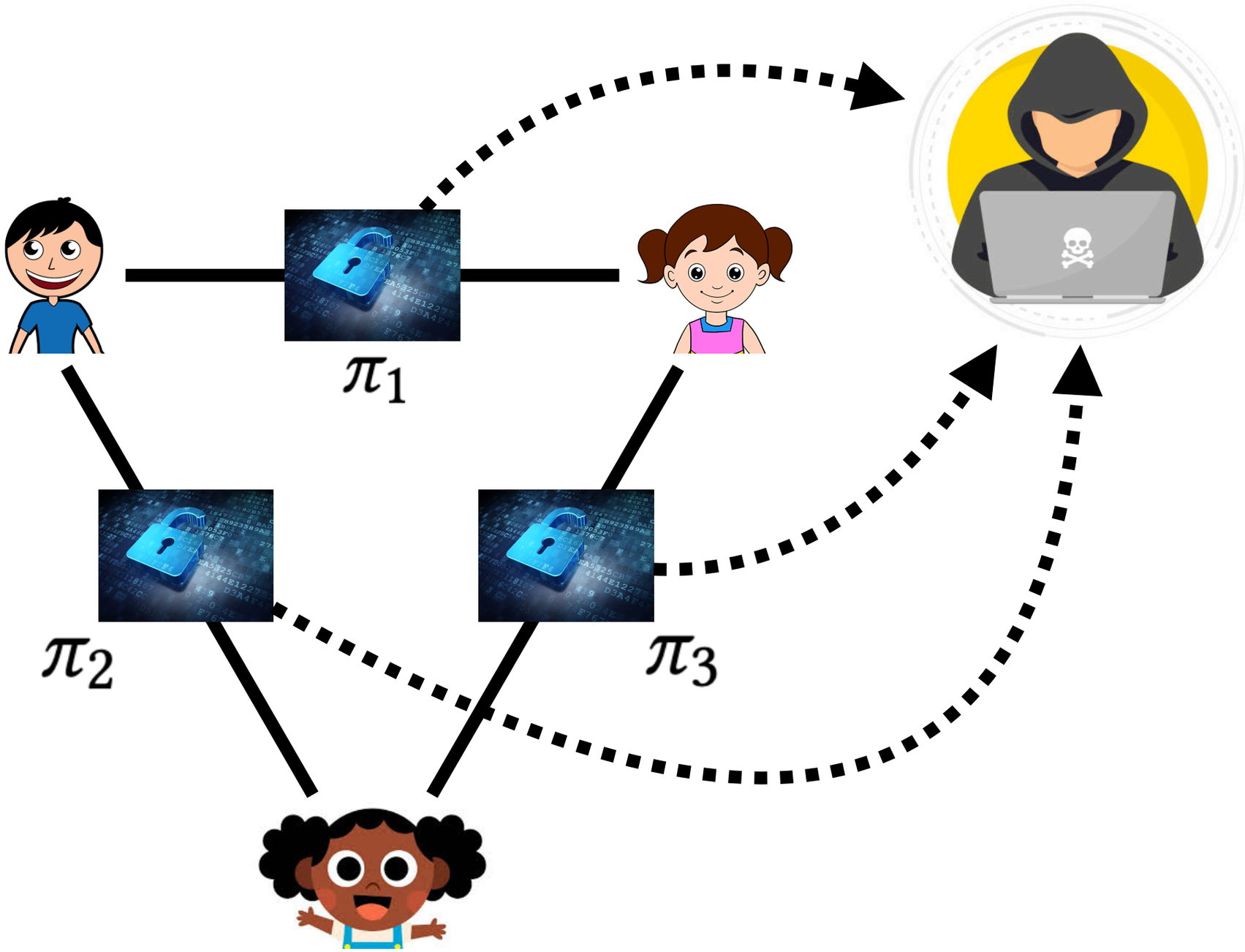


Cryptographic Protocols

are also distributed protocols!

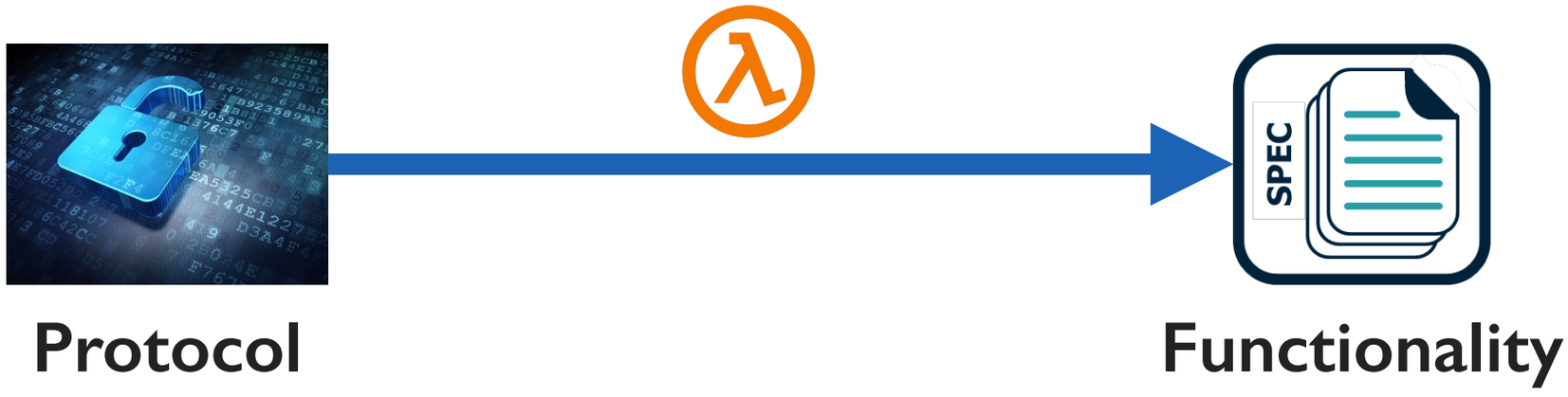
SSL/TLS



Universal Composability (UC)

Protocol

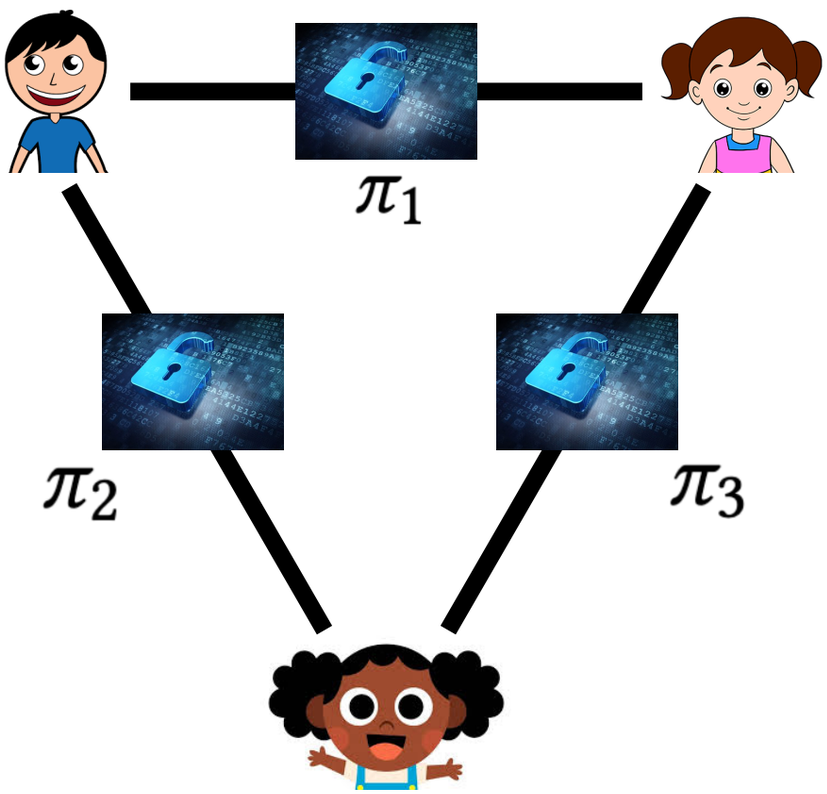
Universal Composability (UC)



Universal Composability (UC)

Protocol

Functionality



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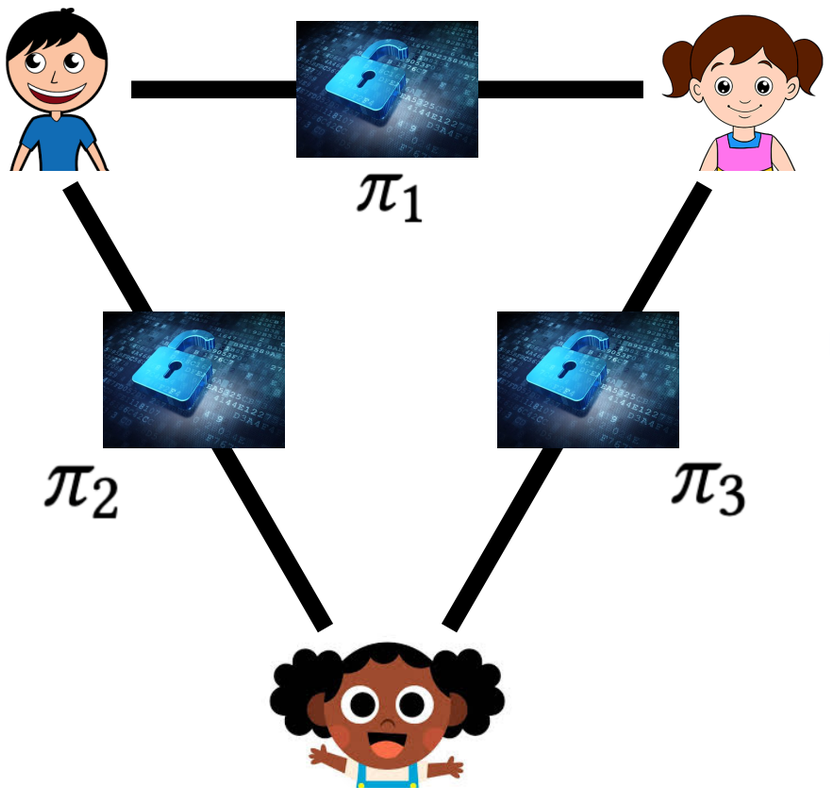

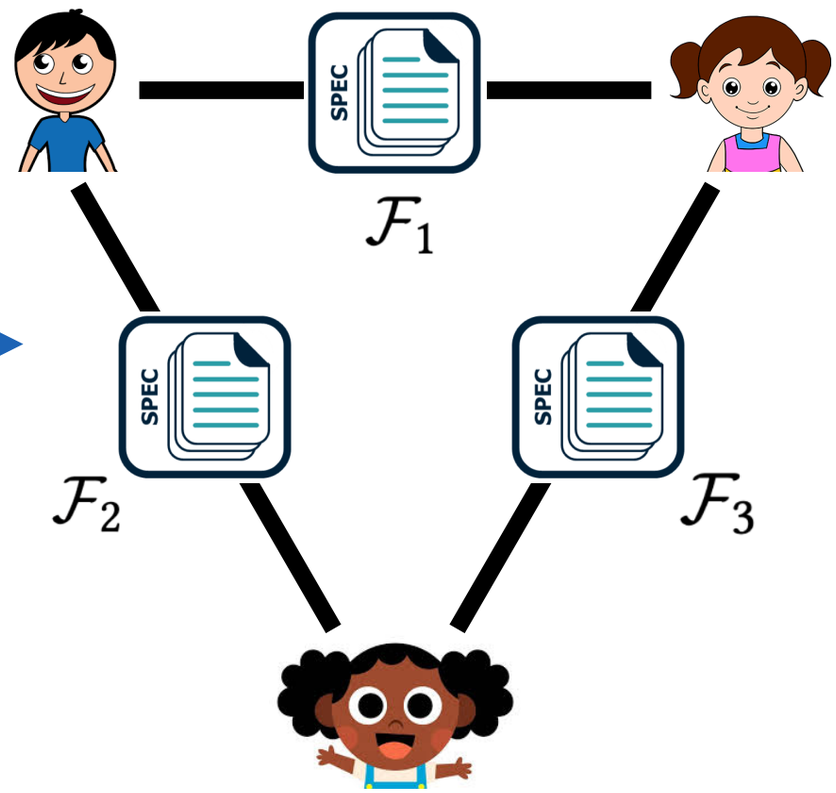

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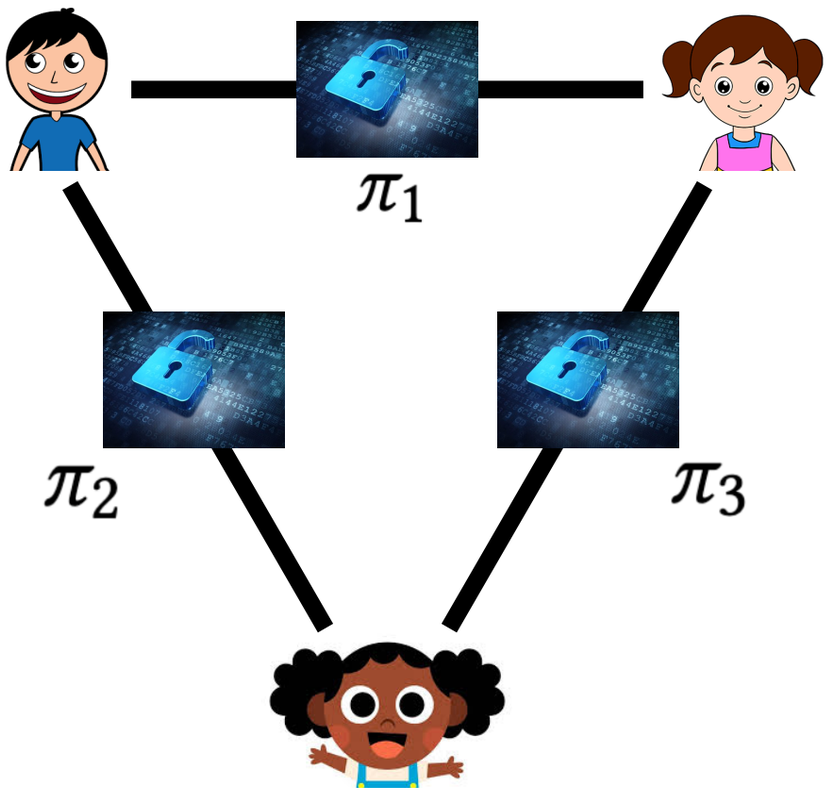

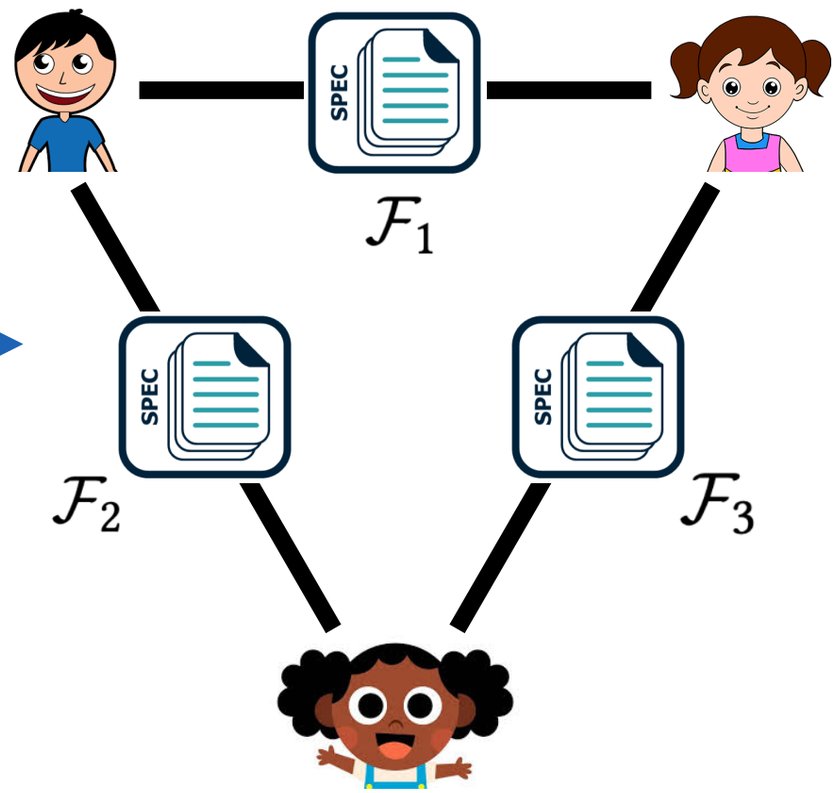

How to ensure resource-bounded computation?

Industrial Research Impacts

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Program Verifier for
Device Drivers
[CAV '15, ATVA '17]

ships as part of
Static Driver Verifier

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Program Verifier for Device Drivers
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Dust Model Checker for Distributed Protocols

Industrial Research Impacts

Program Verifier for Device Drivers
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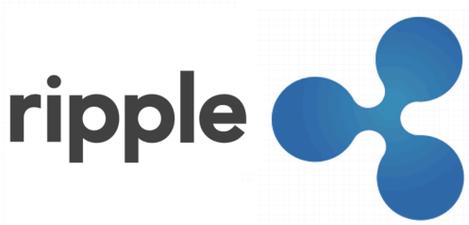
Dust Model Checker for Distributed Protocols

Smart Contract Analysis Techniques
[SAS' 20, CSF '21]



Industrial Research Impacts

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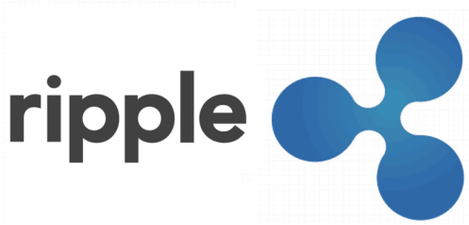


The Dust Project

Dust

Model Checker for Concurrent Rust Programs

The Dust Project

Concurrency Reasoning

Domain-Specific Support

Dust

Model Checker for
Concurrent Rust Programs

The Dust Project

Distributed Databases

Cloud Storage

Network Protocols

Concurrency Reasoning

Domain-Specific Support

Dust

Model Checker for Concurrent Rust Programs

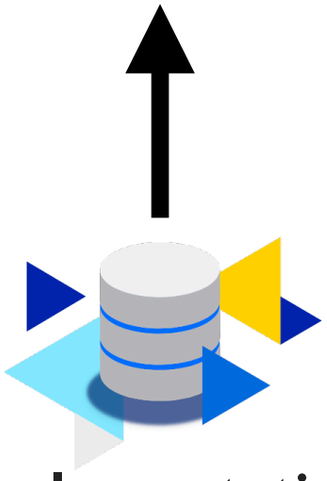
The Dust Model Checker

The Dust Model Checker

Implementation

The Dust Model Checker

Model



Implementation

The Dust Model Checker

<u>Key Idea:</u> Model distributed protocols as concurrency execution graphs

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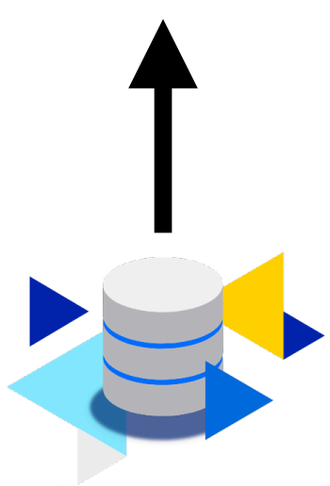

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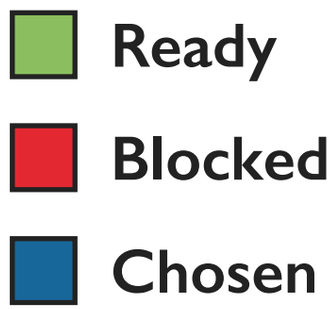

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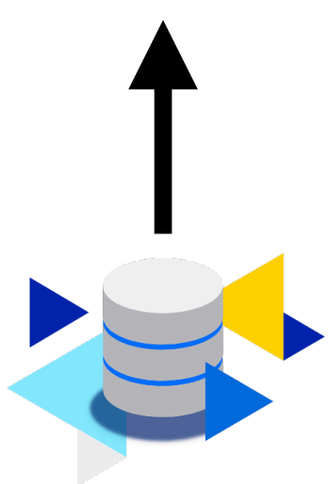

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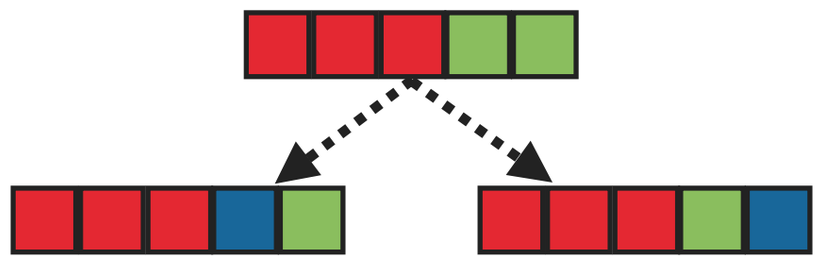

Ready

Blocked

Chosen

The Dust Model Checker

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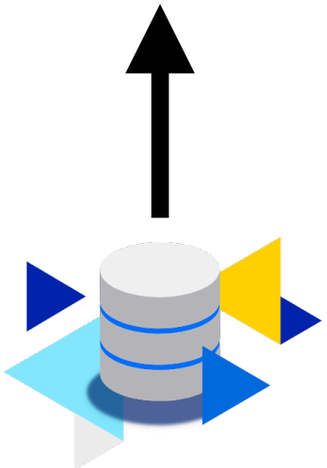

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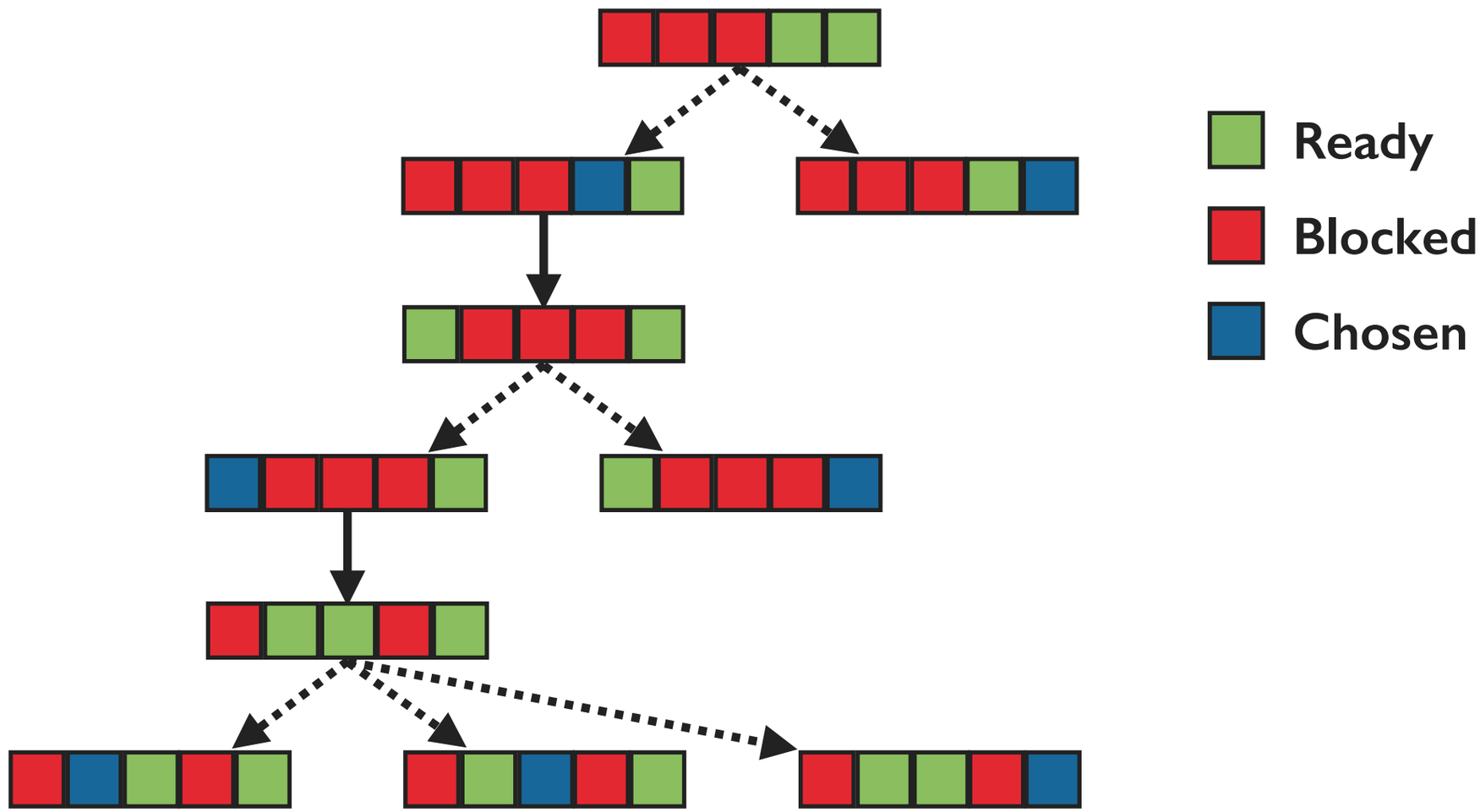

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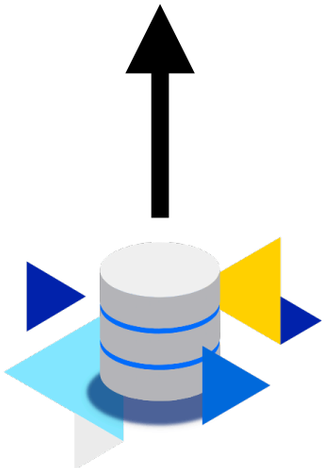

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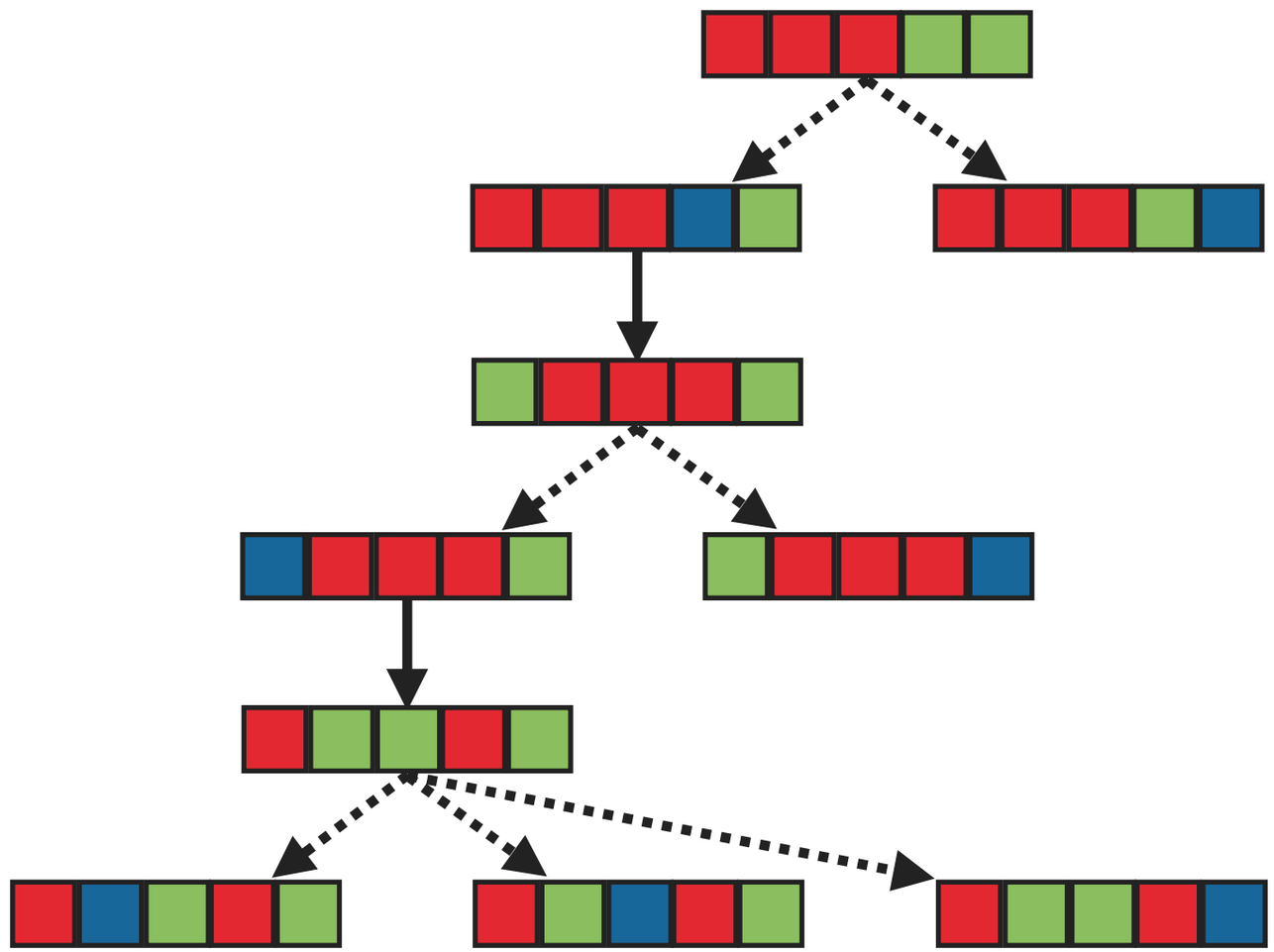


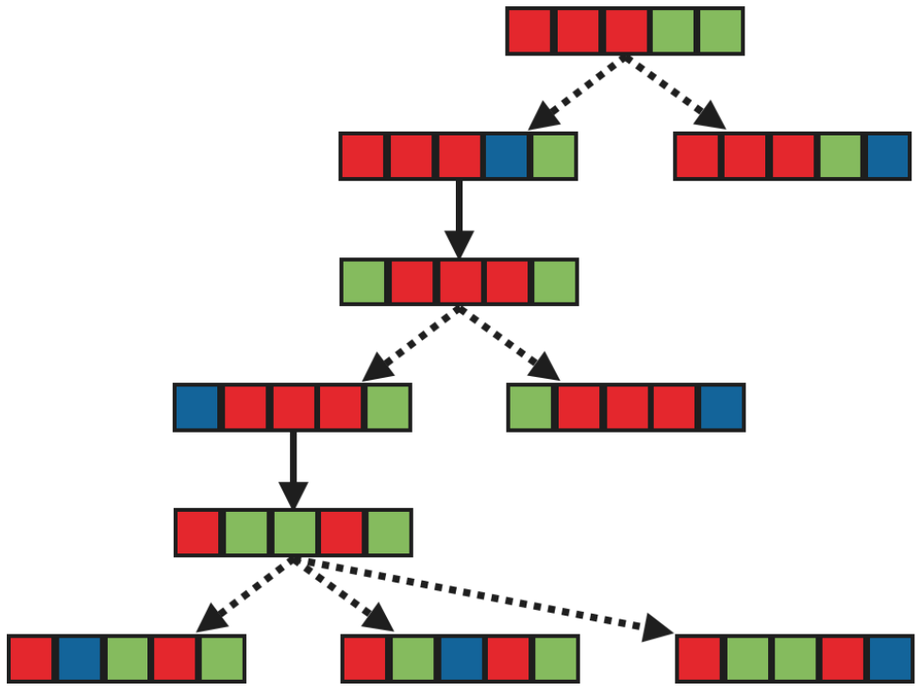
Ready

Blocked

Chosen

State Space Explosion

Session Types Can Help!



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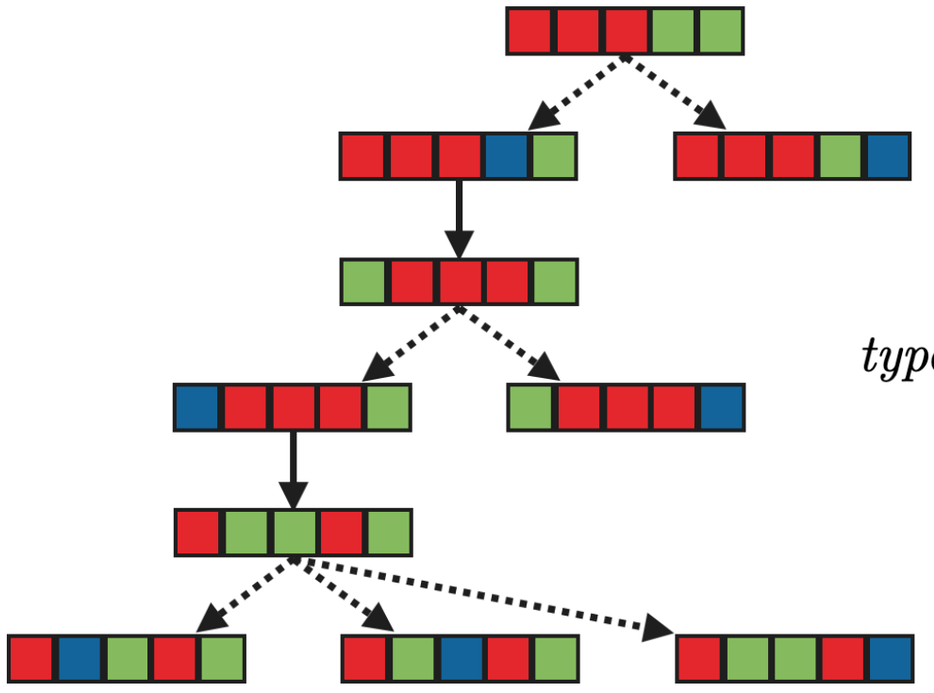

$$\textit{type}\ \text{auction} = \oplus\{\mathbf{running} : \&\{\mathbf{bid} : \text{money} \multimap \text{auction}\},$$
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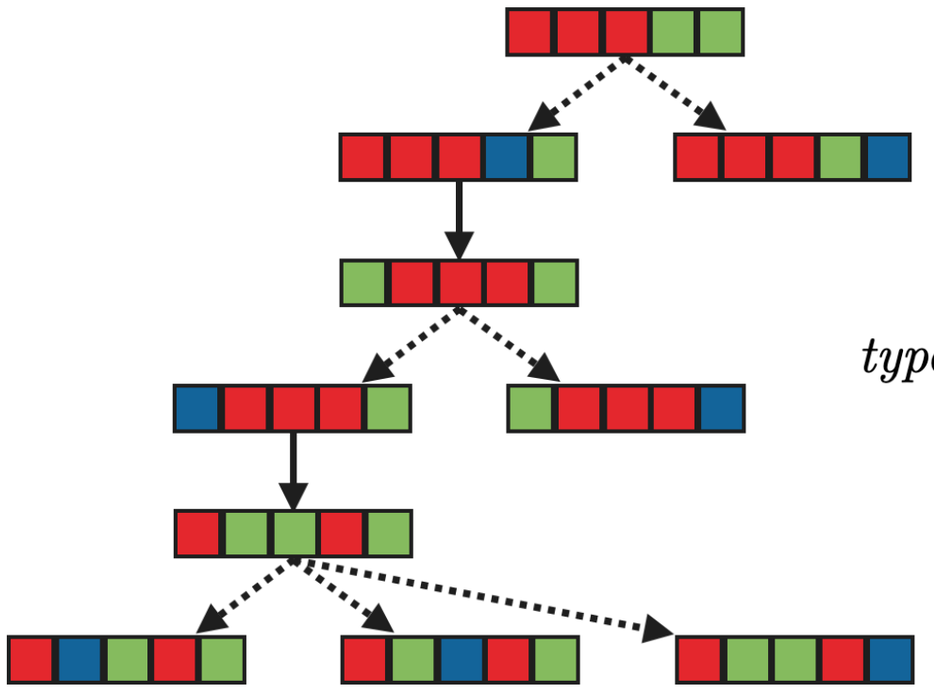

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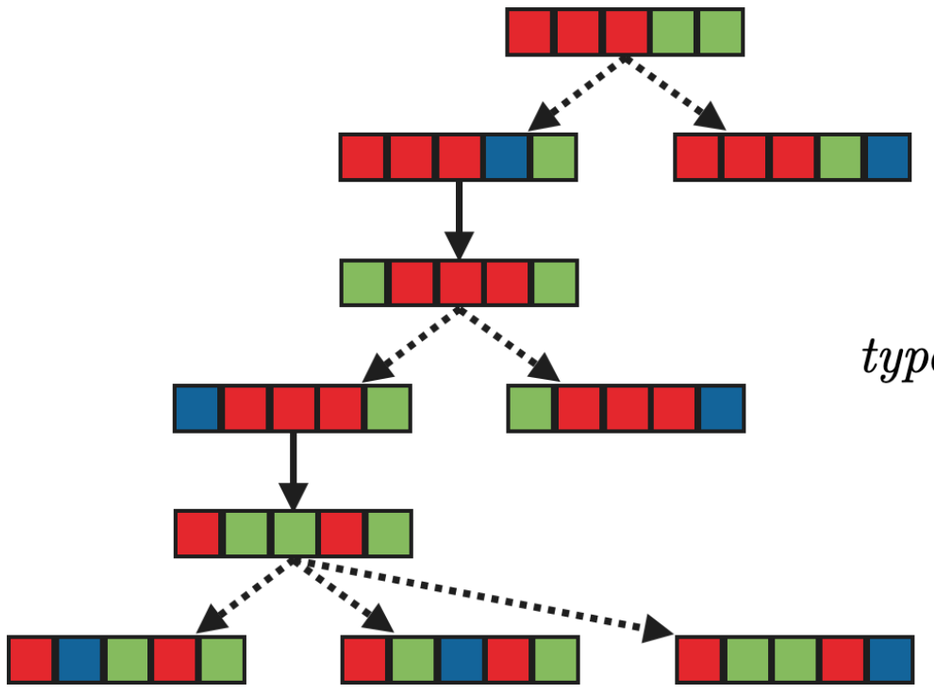
- **Session Types capture communication protocol *with failures!***
- **Many execution traces can be proved *infeasible* via session types**
- ***Eliminate* infeasible traces from execution graph**

Session Types Can Help!



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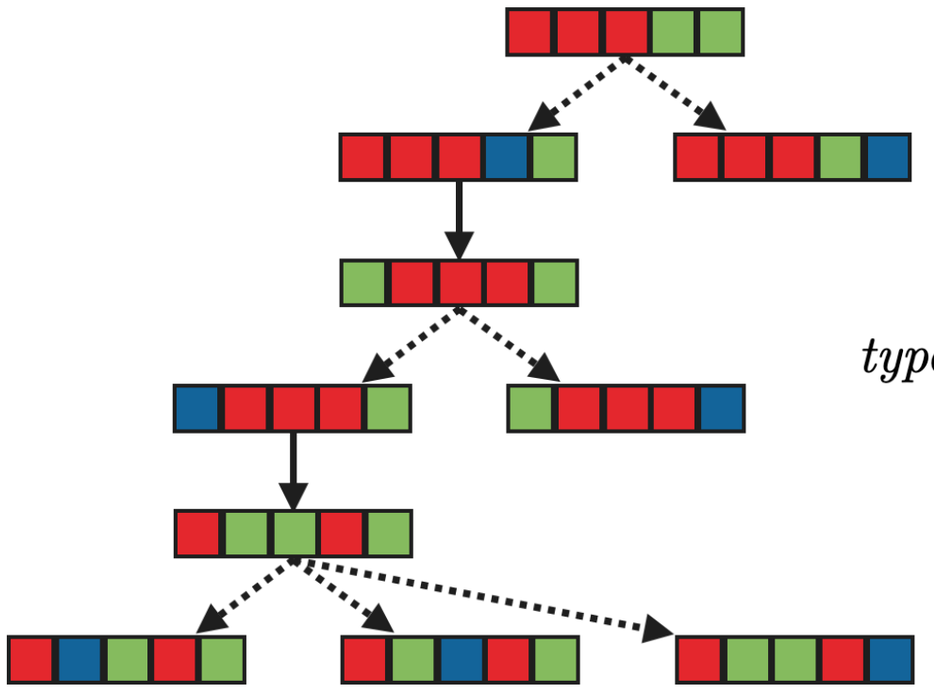

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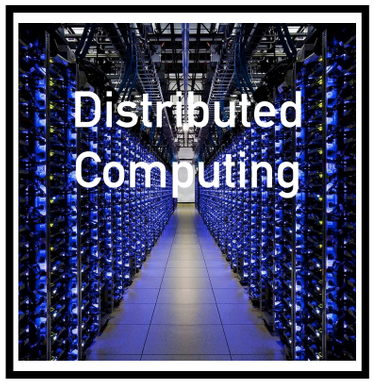
Das et. al. | Parallel Complexity Analysis with Temporal Session Types | ICFP 2018
Bocchi et. al. | Asynchronous Timed Session Types | ESOP 2019
Brun and Dardha | MAGπ: Types for Failure-Prone Communication
Barwell et. Al. | Generalized Multiparty Session Types with Crash-Stop Failures | CONCUR 2022

Conclusion



Nomos

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[LICS '18, SAS '20, CSF '21]

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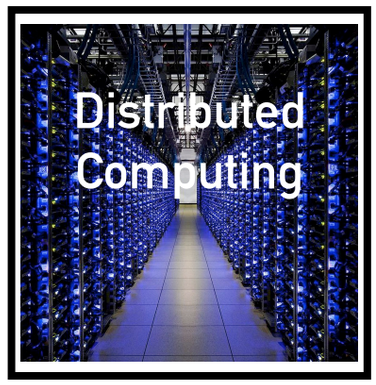
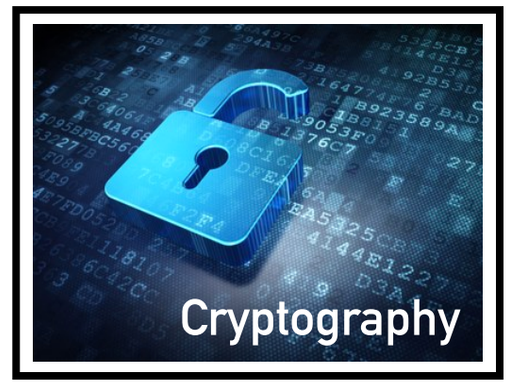
Session Types

Conclusion





Nomos

Resource-Aware Session Types

[LICS '18, SAS '20, CSF '21]

NomosPro

Probabilistic Session Types

[POPL '23]

Rast

Refinement Session Types

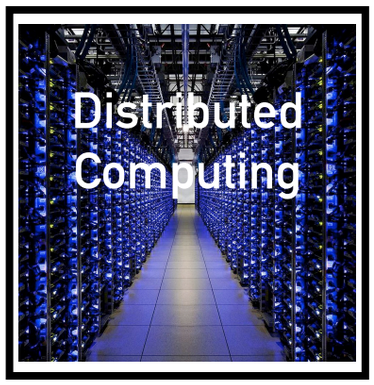
[ICFP '18, FSCD '20, CONCUR '20]

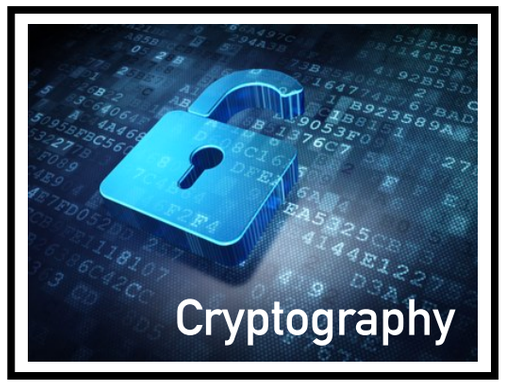
NomosUC

Import Session Types

Session Types

Conclusion





Nomos

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NomosUC

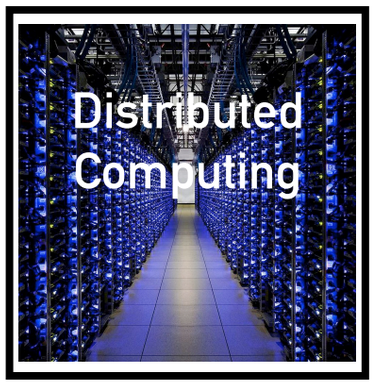
Import Session Types

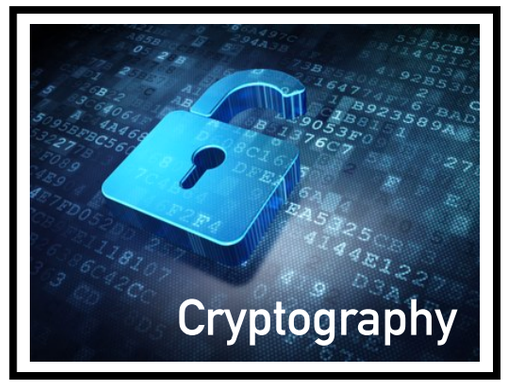
Session Types

Dependent Session Types

Encoding Failures, Timeouts

Conclusion





Nomos
Resource-Aware Session Types
[LICS '18, SAS '20, CSF '21]

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Encoding Failures, Timeouts