Interaction-Oriented Programming for Decentralized Service Engagements

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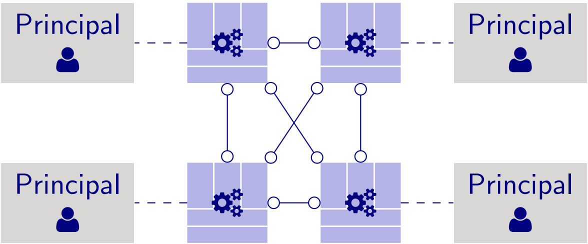
Agents Helping Principals Exercise Autonomy

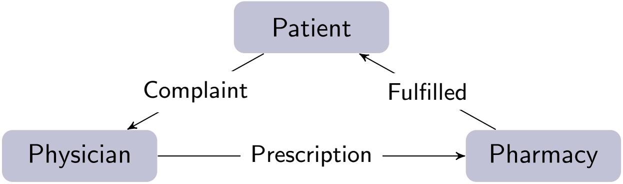
Inherently decentralized



- Each agent reflects the autonomy of its principal
- How can we realize a multiagent system based that accommodates the autonomy of its principals?
  - Does not unduly constrain an agent's decision making
  - Supports flexible interactions
  - Enables loose coupling between agents

Healthcare Application

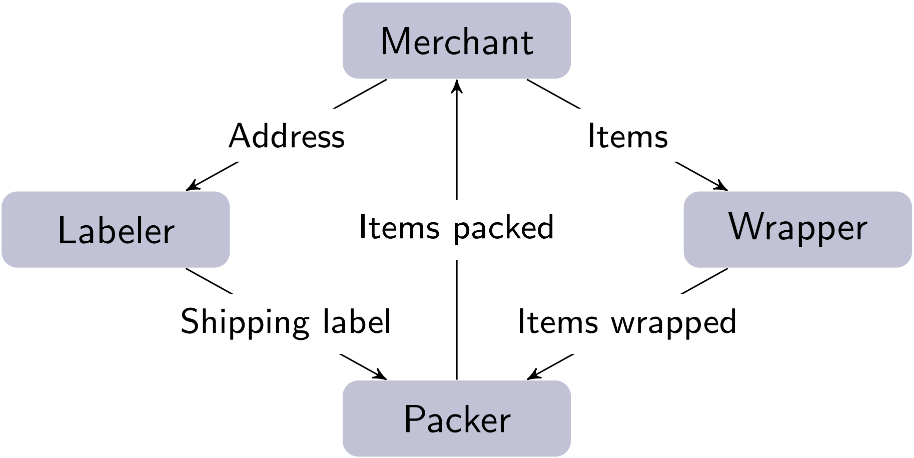
Patient sends a Complaint to Physician, who sends a Prescription to Pharmacy, who sends Fulfill to Patient



- Autonomy means no one need send any message!
- Three parties, not client server
- Healthcare standards: Health Level 7 (HL7), Integrate the Healthcare Enterprise (IHE)
  - Informally described interactions difficult to implement correctly

Purchase Order (PO) Fulfillment Application

Several items in a PO that may be wrapped and packed independently to create a shipment



Asynchronous Communication

Without message ordering guarantees from the communication infrastructure!

- Today: Commonplace to rely on at least FIFO delivery
- Challenge: Coordinate decentralized computation without assuming ordered delivery

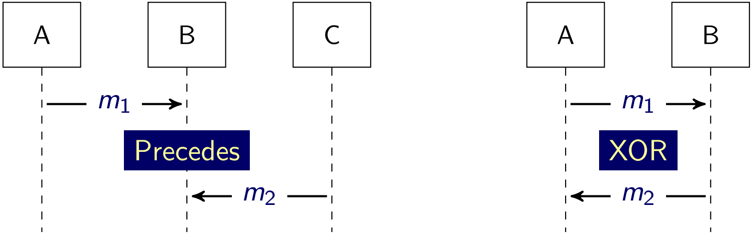
Interaction-Oriented Methodology

Lucid hi-fi computational abstractions for engineering sociotechnical systems

- Engineer a system by composing declarative specifications of interactions
  - Strictly without considering agents (endpoint implementations)
- Engineer an agent on the basis of those specifications
  - Strictly without considering other agents

Traditional Specifications: Procedural

Low-level, over-specified protocols, easily wrong



- Traditional approaches
  - Emphasize arbitrary ordering and occurrence constraints
  - Then work hard to deal with those constraints
- Our philosophy: The Zen of Distributed Computing
  - Necessary ordering constraints fall out from *causality*
  - Necessary occurrence constraints fall out from *integrity*
  - Unnecessary constraints: simply *ignore* such

Properties of Participants

- Autonomy
- Myopia
  - All choices must be local
  - Correctness must not rely on future interactions
- Heterogeneity: local $\neq$ internal
  - Local state (projection of global state, which is stored nowhere)
    - Public or observable
    - Typically, must be revealed for correctness
  - Internal state
    - Private
    - Must never be revealed: to avoid false coupling
- Shared nothing representation of local state
  - Enact via messaging

BSPL, the Blindingly Simple Protocol Language

Main ideas

- Only *two* syntactic notions
  - Declare a message schema: as an atomic protocol
  - Declare a composite protocol: as a bag of references to protocols
- Parameters are central
  - Provide a basis for expressing meaning in terms of bindings in protocol instances
  - Yield unambiguous specification of compositions through public parameters
  - Capture progression of a role's knowledge
  - Capture the completeness of a protocol enactment
  - Capture uniqueness of enactments through keys
- Separate structure (parameters) from meaning (bindings)
  - Capture many important constraints purely structurally

Key Parameters in BSPL

Marked as ⌜key⌝

- All the key parameters *together* form the key
- Each protocol must define at least one key parameter
- Each message or protocol reference must have at least one key parameter in common with the protocol in whose declaration it occurs
- The key of a protocol provides a basis for the uniqueness of its enactments

Parameter Adornments in BSPL

Capture the essential causal structure of a protocol (for simplicity, assume all parameters are strings)

- ⌜in⌝: Information that must be provided to instantiate a protocol
  - Bindings must exist locally in order to proceed
  - Bindings must be produced through some other protocol
- ⌜out⌝: Information that is generated by the protocol instances
  - Bindings can be fed into other protocols through their ⌜in⌝ parameters, thereby accomplishing composition
  - A standalone protocol must adorn all its public parameters ⌜out⌝
- ⌜nil⌝: Information that is absent from the protocol instance
  - Bindings must not exist

Protocol in BSPL: Main Ideas

- Declarative
  - No control flow, no control state
- Information-based
  - Specifies the computation of distributed information object
    - Message specification is atomic protocol
  - Specified via parameters
- Explicit causality
  - The messages an agent can send depends upon what it knows
  - Via parameter adornments ⌜out⌝, ⌜in⌝, ⌜nil⌝
- Integrity
  - Agent only sends messages that preserve consistency of objects
  - Via key constraints
- Asynchronous messaging
- Requires no ordering from infrastructure
- Composition and verification

The *Initiate* protocol

```
Initiate {
 role B, S
 parameter out ID key, out item

 B ↦ S: rfq[out ID key, out item]
}
```

The *Initiate* protocol

```
Initiate {
 role B, S
 parameter out ID key, out item

 B ↦ S: rfq[out ID key, out item]
}
```

Initiate (virtual)

ID	item

B:rfq

ID	item

S:rfq

ID	item

The *Initiate* protocol

```
Initiate {
 role B, S
 parameter out ID key, out item

 B ↦ S: rfq[out ID key, out item]
}
```

Initiate (virtual)

ID	item
1	fig

B:rfq

ID	item
1	fig

S:rfq

ID	item

The *Initiate* protocol

```
Initiate {
 role B, S
 parameter out ID key, out item

 B ↦ S: rfq[out ID key, out item]
}
```

Initiate (virtual)

ID	item
1	fig
5	jam

B:rfq

ID	item
1	fig
5	jam

S:rfq

ID	item

The *Initiate* protocol

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S:rfq

ID	item
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}
```

Initiate (virtual)

ID	item
1	fig
5	jam

B:rfq

ID	item
1	fig
5	jam
×1	apple

S:rfq

ID	item
5	jam

The *Initiate* protocol

```
Initiate {
 role B, S
 parameter out ID key, out item

 B ↦ S: rfq[out ID key, out item]
}
```

Initiate (virtual)

ID	item
1	fig
5	jam
8	fig

B:rfq

ID	item
1	fig
5	jam
8	fig

S:rfq

ID	item
5	jam

The *Offer* Protocol

```
Offer {
 role B, S
 parameter out ID key, out item, out price

 B ↦ S: rfq[out ID, out item]
 S ↦ B: quote[in ID, in item, out price]
}
```

The *Offer* Protocol

```
Offer {
 role B, S
 parameter out ID key, out item, out price

 B ↦ S: rfq[out ID, out item]
 S ↦ B: quote[in ID, in item, out price]
}
```

Offer (virtual)

ID	item	price
1	fig	

B:rfq

ID	item
1	fig

B:quote

ID	item	price

S:rfq

ID	item
1	fig

S:quote

ID	item	price

The *Offer* Protocol

```
Offer {
 role B, S
 parameter out ID key, out item, out price

 B ↦ S: rfq[out ID, out item]
 S ↦ B: quote[in ID, in item, out price]
}
```

Offer (virtual)

ID	item	price
1	fig	10

B:rfq

ID	item
1	fig

B:quote

ID	item	price

S:rfq

ID	item
1	fig

S:quote

ID	item	price
1	fig	10

The *Offer* Protocol

```
Offer {
 role B, S
 parameter out ID key, out item, out price

 B ↦ S: rfq[out ID, out item]
 S ↦ B: quote[in ID, in item, out price]
}
```

Offer (virtual)

ID	item	price
1	fig	10

B:rfq

ID	item
1	fig

B:quote

ID	item	price
1	fig	10

S:rfq

ID	item
1	fig

S:quote

ID	item	price
1	fig	10

The *Offer* Protocol

```
Offer {
 role B, S
 parameter out ID key, out item, out price

 B ↦ S: rfq[out ID, out item]
 S ↦ B: quote[in ID, in item, out price]
}
```

Offer (virtual)

ID	item	price
1	fig	10

B:rfq

ID	item
1	fig

B:quote

ID	item	price
1	fig	10

S:rfq

ID	item
1	fig

S:quote

ID	item	price
1	fig	10
×4	fig	10

The *Decide Offer* Protocol

Choice: *accept* and a *reject* with the same ID *cannot* both occur

```
Decide Offer {
 role B, S
 parameter out ID key, out item, out price, out decision

 B ↦ S: rfq[out ID, out item]
 S ↦ B: quote[in ID, in item, out price]

 B ↦ S: accept[in ID, in item, in price, out decision]
 B ↦ S: reject[in ID, in item, in price, out decision]
}
```

The *Decide Offer* Protocol

Choice: *accept* and a *reject* with the same ID *cannot* both occur

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Decide Offer {
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 B ↦ S: accept[in ID, in item, in price, out decision]
 B ↦ S: reject[in ID, in item, in price, out decision]
}
```

Decide Offer (virtual)

ID	item	price	decision
1	fig	10	

B:rfq

ID	item
1	fig

B:quote

ID	item	price
1	fig	10

B:accept

ID	item	price	decision

B:reject

ID	item	price	decision

The *Decide Offer* Protocol

Choice: *accept* and a *reject* with the same ID *cannot* both occur

```
Decide Offer {
 role B, S
 parameter out ID key, out item, out price, out decision

 B ↦ S: rfq[out ID, out item]
 S ↦ B: quote[in ID, in item, out price]

 B ↦ S: accept[in ID, in item, in price, out decision]
 B ↦ S: reject[in ID, in item, in price, out decision]
}
```

Decide Offer (virtual)

ID	item	price	decision
1	fig	10	nice

B:rfq

ID	item
1	fig

B:quote

ID	item	price
1	fig	10

B:accept

ID	item	price	decision
1	fig	10	nice

B:reject

ID	item	price	decision

The *Decide Offer* Protocol

Choice: *accept* and a *reject* with the same ID *cannot* both occur

```
Decide Offer {
 role B, S
 parameter out ID key, out item, out price, out decision

 B ↦ S: rfq[out ID, out item]
 S ↦ B: quote[in ID, in item, out price]

 B ↦ S: accept[in ID, in item, in price, out decision]
 B ↦ S: reject[in ID, in item, in price, out decision]
}
```

Decide Offer (virtual)

ID	item	price	decision
1	fig	10	nice

B:rfq

ID	item
1	fig

B:quote

ID	item	price
1	fig	10

B:accept

ID	item	price	decision
1	fig	10	nice

B:reject

ID	item	price	decision
×1	fig	10	nice

The *Purchase* Protocol

```
Purchase {
 role B, S, Shipper
 parameter out ID key, out item, out price, out outcome
 private address, resp

 B ↦ S: rfq[out ID, out item]
 S ↦ B: quote[in ID, in item, out price]
 B ↦ S: accept[in ID, in item, in price, out address, out resp]
 B ↦ S: reject[in ID, in item, in price, out outcome, out resp]

 S ↦ Shipper: ship[in ID, in item, in address]
 Shipper ↦ B: deliver[in ID, in item, in address, out outcome]
}
```

- *reject* conflicts with *accept* on resp (a *private* parameter)
- *reject* or *deliver* must occur for completion (to bind outcome)

Standing Order

As in insurance claims processing

```
Insurance−Claims {
 role Vendor (V), Subscriber (S)
 parameter out pID key, out cID key, out claim, out response

 Create−Policy(V, S, out pID, out details)
 S ↦ V: claimRequest[in pID, out cID, out claim]
 V ↦ S: claimResponse[in pID, in cID, out response]
}
```

- Illustrates composite keys
  - A policy (identified by a binding for pID) may be associated with multiple claims (each identified by a binding for cID)
- Composes protocol Create-Policy, which produces bindings for pID

Realizing BSPL via Local State Transfer (LoST)

Think of the message logs you want

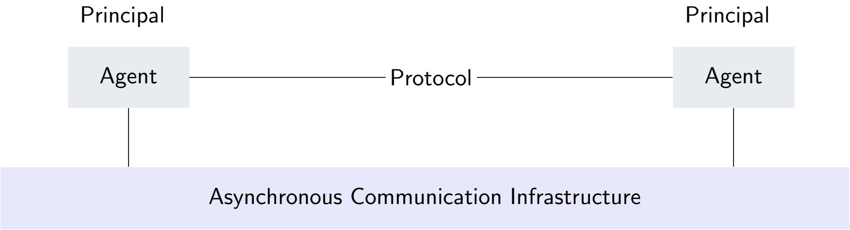
- For each role
  - For each message that it sends or receives
    - Maintain a *local* relation of the same schema as the message
- Receive and store any message provided
  - It is not a duplicate
  - Its integrity checks with respect to parameter bindings
  - Garbage collect expired sessions: requires additional annotations
- Send any unique message provided
  - Parameter bindings agree with previous bindings for the same keys for ⌜in⌝ parameters
  - No bindings for ⌜out⌝ and ⌜nil⌝ parameters exist

Information Centrism

Characterize each interaction purely in terms of information

- Explicit causality
  - Flow of information coincides with flow of causality
  - No hidden control flows
  - No backchannel for coordination
- Keys
  - Uniqueness
  - Basis for completion
- Integrity
  - Parameter has only one value relative to the key
- Immutability
  - Durability
  - Robustness: insensitivity to
    - Reordering by infrastructure
    - Retransmission: one delivery is all it needs

Ideal Protocol-Based System Architecture



- Constraints
  1. Agent ensures the correctness of its emissions. To do so, it needs nothing but its local state (history of prior emissions and receptions)
  2. The reception of any message is correct, if it was emitted correctly
  3. Asynchrony: Emissions nonblocking; receptions nondeterministic
     - No ordered delivery guarantee needed from infrastructure.
  4. The protocol is the complete operational specification of the system
- Assumption: Infrastructure delivers only sent messages
  - No guaranteed delivery assumed

Comparing LoST and ReST

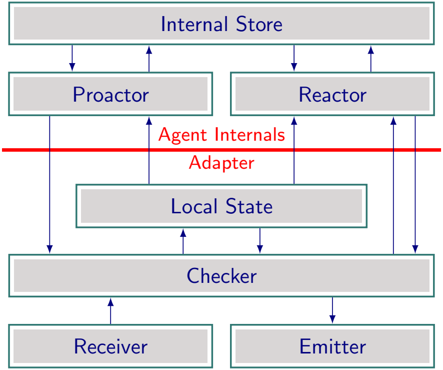
	ReST	*LoST*
Modality	Two-party; client-server; synchronous	Multiparty interactions; peer-to-peer; asynchronous
Computation	Server computes definitive resource state	Each party computes its definitive local state and the parties collaboratively and (potentially implicitly) compute the definitive interaction state
State	Server maintains no client state	Each party maintains its local state and, implicitly, the relevant components of the states of other parties from which there is a chain of messages to this party

Comparing LoST and ReST

	ReST	*LoST*
Transfer	State of a resource, suitably represented	Local state of an interaction via parameter bindings, suitably represented
Idempotent	For some verbs, especially GET	Always; repetitions are guaranteed harmless
Caching	Programmer can specify if cacheable	Always cacheable
Uniform interface	GET, POST, . . .	⌜in⌝, ⌜out⌝, ⌜nil⌝
Naming	Of resources via URIs	Of interactions via (composite) keys, whose bindings could be URIs

Decentralized Applications on FaaS Platforms

Protocol + FaaS = highly modular and concurrent agent out of the box
Developer focuses on business logic
Implemented on AWS Lambda



- Decision-making components, Proactor and Reactor
- Many instances of each as FaaS functions
- Each Reactor handles one message schema (encoded in JSON)
- Unique Checker for each agent
- Deployment: configuration file per agent referring to *layers* for components and resources

Implementation on Amazon Web Services

Using the term *stack* instead of *service* to avoid confusion

- Serverless Framework manages the configuration of multiple resources
- Stack: a declarative specification of resources to be interpreted
  - Locally using Serverless Framework tools
  - Via a cloud deployment system, e.g., CloudFormation
- Separate stack for each agent to avoid coupling them unnecessarily: generally, agents are provided by different organizations
- Map roles to endpoints, as below


```
{
  "Merchant": "https://5yo8ouXXXX.execute-api.us-east-1.amazonaws.com/merchant/messages",
  "Labeler": "https://awj8rrXXXX.execute-api.us-east-1.amazonaws.com/labeler/messages",
  "Wrapper": "https://23y4xcXXXX.execute-api.us-east-1.amazonaws.com/wrapper/messages",
  "Packer": "https://akuf0nXXXX.execute-api.us-east-1.amazonaws.com/packer/messages"
}
```

Layer for the Checker Component

```
checker:
  path: layer # required, path to layer contents on disk
  name: PoSCheckerLayer # optional, Deployed Lambda layer
      name
  description: Layer for sharing the PoS checker module #
      optional, Description to publish to AWS
  licenseInfo: GPLv3 # optional
  package:
    include:
      - '!./**'
      - checker.py
```

- Common component in our architecture

JSON Specification of the *Logistics* Protocol

```
{
  "name": "Logistics",
  "type": "protocol",
  "parameters": ["orderID", "itemID", "item", "status"],
  "keys": ["orderID", "itemID"],
  "ins": [],
  "outs": ["orderID", "itemID", "item", "status"],
  "nils": [],
  "roles": ["Merchant", "Wrapper", "Labeler", "Packer"],
  "messages": {
    "RequestLabel": {
      "name": "Logistics/RequestLabel",
      "type": "message",
      "parameters": ["orderID", "address"],
      "keys": ["orderID"],
      "ins": [],
      "outs": ["orderID", "address"],
      "nils": [],
      "to": "Labeler",
      "from": "Merchant"
    },
    ...
```

Merchant's Checker Specification

```
MerchantChecker:
  name: MerchantChecker
  handler: /opt/checker.lambda_handler
  layers:
    - ${cf:pos-components-dev.CheckerLayerExport}
    - ${cf:pos-components-dev.DepsLayerExport}
    - ${cf:logistics-dev.ConfigurationLayerExport}
  reservedConcurrency: 1
```

- Declares a function `MerchantChecker`, which uses `CheckerLayerExport` to load the checker code, which includes the Checker, and loads the configuration layer

MERCHANT's Reactor Specification for the *Packed* Message

```
PackedReactor:
  name: Merchant_Packed_Reactor
  handler: packed_reactor.lambda_handler
  package:
    include:
      - packed_reactor.py
```

- Identifies its Lambda handler
- Identifies the implementation code to load

MERCHANT Package Specification

```
package:
  individually: true
  include:
    - '!**'
    - reactors.json
```

- Registers the Reactor by adding `reactors.json` for MERCHANT
- Specifies what to include and exclude
- MERCHANT's Reactor mapping is below:


```
{
  "Logistics/Packed":
        "arn:aws:lambda:us-east-1:834106683512:function:Merchant_Packed_Reactor"
}
```

Packer's Reactor for the *Wrapped* Message (Partial)

```
def lambda_handler(event, context): # wrapped reactor
    message = event["message"]
    enactment = event["enactment"]
    labeled_msg = next((m for m in enactment if m.get("label")),
        None)
    if labeled_msg:
        # send packed notification for item
        payload = {
            "type": "send",
            "to": "Merchant",
            "message": {
                "orderID": message["orderID"],
                "itemID": message["itemID"],
                "wrapping": message["wrapping"],
                "label": labeled_msg["label"],
                "status": "packed",
            },
        }
        payload = json.dumps(payload).encode("utf-8")
        print("Sending Packed: {}".format(payload))
        response = client.invoke(
            FunctionName="PackerChecker",
            ...
```

MERCHANT's Proactor Specification

```
# functions
order:
  handler: order.writeToDynamo
  events:
    - httpApi: POST /orders  # to receive customer orders
  package:
    include:
      - order.py
PO_proactor:
  handler: PO_proactor.get_order_proactor
  events:
    - stream:
      type: DynamoDB
      arn:
        Fn::GetAtt: [ordersTable, StreamArn]
  package:
    include:
      - PO_proactor.py
```

- Proactor produces events or respond to outside events

Evaluation on AWS Lambda: Transaction Time and Throughput

- Asynchronously submit 1,000 POs (1–4 items) for *Fulfillment*
- Set all DynamoDB tables to autoscale, with no throttling of requests
- Normal setting: no delay
- Delayed setting: 1s delay to simulate heavier processing
- Delay: analyze the merchant agent's message timestamps

Experiment	PO Duration		Throughput	
	Mean (s)	St. Dev. (s)	POs/s	Items/s
Normal	266.51	51.45	1.23	2.37
Delayed	267.27	46.45	1.21	2.34

- Reactor without delay takes 1ms to 380ms but delay of 1,000ms has little effect—low effect size of difference (Cohen's d = 0.015)

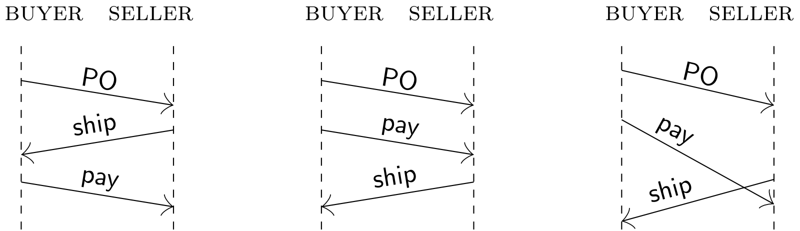
Evaluation on AWS Lambda: Concurrency

Concurrent instances of Lambda functions via AWS CloudWatch monitoring console

- Deserv takes advantage of automatic scaling in FaaS
- The Checker and database are potential bottlenecks
- The business computation takes place in the Reactor, however

Component	Number of Instances	
	Normal	Delayed
Receiver	2	2
Reactor	2	13
Emitter	3	5

Multiple Enactments Are Possible and Desirable



(a) Shipment first (b) Payment first (c) Concurrent

- Information-based protocol languages
  - Declarative: based on causality and integrity constraints
  - Produce maximal flexibility compatible with application meaning

Main finding: Information protocols formalized declaratively make possible optimizations that are unavailable for traditional protocol languages

Protocol: Purchase with Cancellation

Causality and integrity are captured via in, out, and nil

```
protocol PO Pay Cancel Ship {
  roles B, S
  parameters out ID key, out item, out price, out outcome
  private pDone, gDone, rescind

  B ↦ S: PO [out ID key, out item, out price]

  B ↦ S: cancel [in ID key, nil pDone, nil gDone, out rescind]

  B ↦ S: pay [in ID key, in price, in item, out pDone]

  S ↦ B: ship [in ID key, in item, nil rescind, out gDone]

  S ↦ B: cancelAck [in ID key, in rescind, nil gDone, out
     outcome]

  S ↦ B: payAck [in ID key, in pDone, out outcome]
}
```

Generating a Tableau

- A tableau node captures the enactment so far
- Any enabled emission or reception can take place next
  - Explosion of possibilities; most are irrelevant variants
- Some are relevant alternatives: enabled emissions may become disabled
- All enabled receptions remain enabled (until they occur)

Generate a reduced tableau $\Rightarrow$
All logically distinct possibilities are retained
Superfluous variants are reduced

Causal Relations Between Messages

Derived entirely from their parameters and how they are adorned

Two messages with a common parameter:

- Some message with ⌜out⌝ must precede a message with ⌜in⌝
  - Directly endows (necessary precursor): when only one message has ⌜out⌝
- Receiving message with ⌜in⌝ enables another with ⌜in⌝, disables ⌜out⌝ and ⌜nil⌝
- Sending or receiving message with ⌜out⌝ enables another with ⌜in⌝, disables ⌜out⌝ and ⌜nil⌝
- Message with ⌜nil⌝ has no effect

Chaining the above:

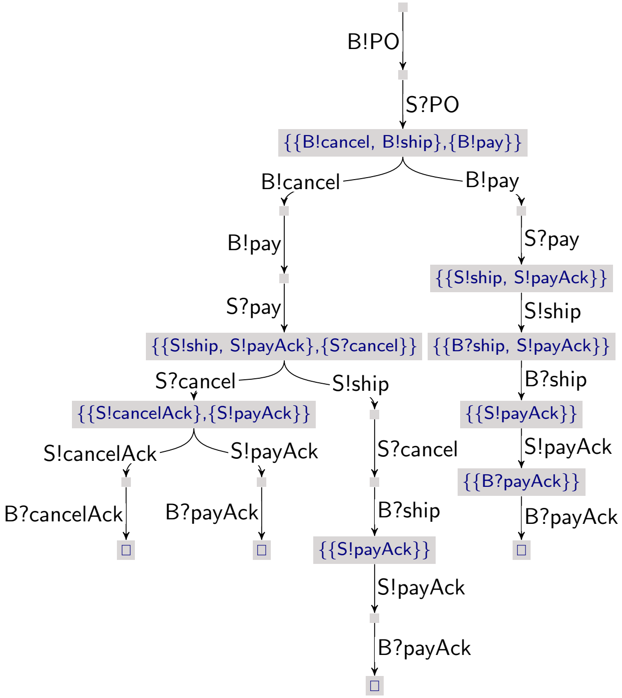
- Enablement: chain of one or more direct enablements
- Tangles with: Doesn't endow (make possible) a message, and disables a message or disables a causal precursor of the message
- Incompatible: tangles with and at least one of them an emission

Reduction Method

Sensitive observations (emissions or receptions): if they may disable others or be disabled by others

- Expand tableau using nonsensitive observations in arbitrary order
- If only sensitive observations
  - Produce partitions heuristically (approximate vertex cover)
  - Create one branch for each compatible set in the partition
  - Develop each branch with an arbitrary member of the set
- Iterate until all branches end or hit an inconsistency

- To verify a property: assert suitable proposition at root
- Stop tableau expansion upon contradiction
- Here: complete tableau for illustration
- 22 nodes instead of 1,495



Performance Comparison

Major improvements on practical protocols
Protocol listings are online or in works cited from the Tango paper

	No Branch Reductions			Tango		
Protocol	**Nodes**	**Branches**	**Time**	**Nodes**	**Branches**	**Time**
PO Pay Cancel Ship	1,495	490	655 ms	22	4	8 ms
Block Contra	1,802	612	636 ms	14	2	8 ms
Independent	453	90	157 ms	11	1	3 ms
NetBill (e-commerce)	4,097	1,246	2,688 ms	62	8	38 ms
HL7 Create Lab Order	59,259	17,814	70,953 ms	69	14	76 ms

Tango: Precisely captures tanglements based on information protocols to justify strong optimizations

Discussion

Demonstrate how to achieve decentralization, avoid client-server programming, while taking advantage of serverless computing

- IOP modularizes service systems
  - Separates agents from one another
  - Coupled only to the extent as specified in a protocol
  - Information model supports asynchrony
- Deserv unifies protocol-based programming of service engagements with serverless computing
  - Each agent is a composition of microservices
  - Immutability of information is naturally compatible with functional programming
- Tango exploits causality to reduce complexity of formal verification

Directions and Thanks

- Implementation: `https://gitlab.com/masr`
- Tools address
  - Formal verification of protocols
  - Fault tolerant agents as microservices
  - Serverless computing
  - IoT applications
  - Blockchain implementation of contracts
- Directions: Enhanced tooling and evaluation
- Collaborators welcome!
- Thanks!
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