Globality

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Reflecting joint work with Luís Caires, Giorgio Ghelli, Andrew D. Gordon.

Introduction

- We are building infrastructure that allows us to be connected “everywhere all the time”.
  - Global wired and wireless speech and data networks.
  - *Local / reactive / synchronous / connected*.
- At the same time, we are building infrastructure that allows us to be isolated and protected from intrusion.
  - Answering machines, crypto, Great FireWall of China.
  - *Remote / deferred / asynchronous / blocked*.
- We cannot have it both ways. We will have to describe what we want to be *local* or *accessible* and we will have to adapt to what must necessarily be *remote* or *inaccessible*.
- All this applies on a very small scale (ad hoc networks), but global networks tend to stretch the imagination.

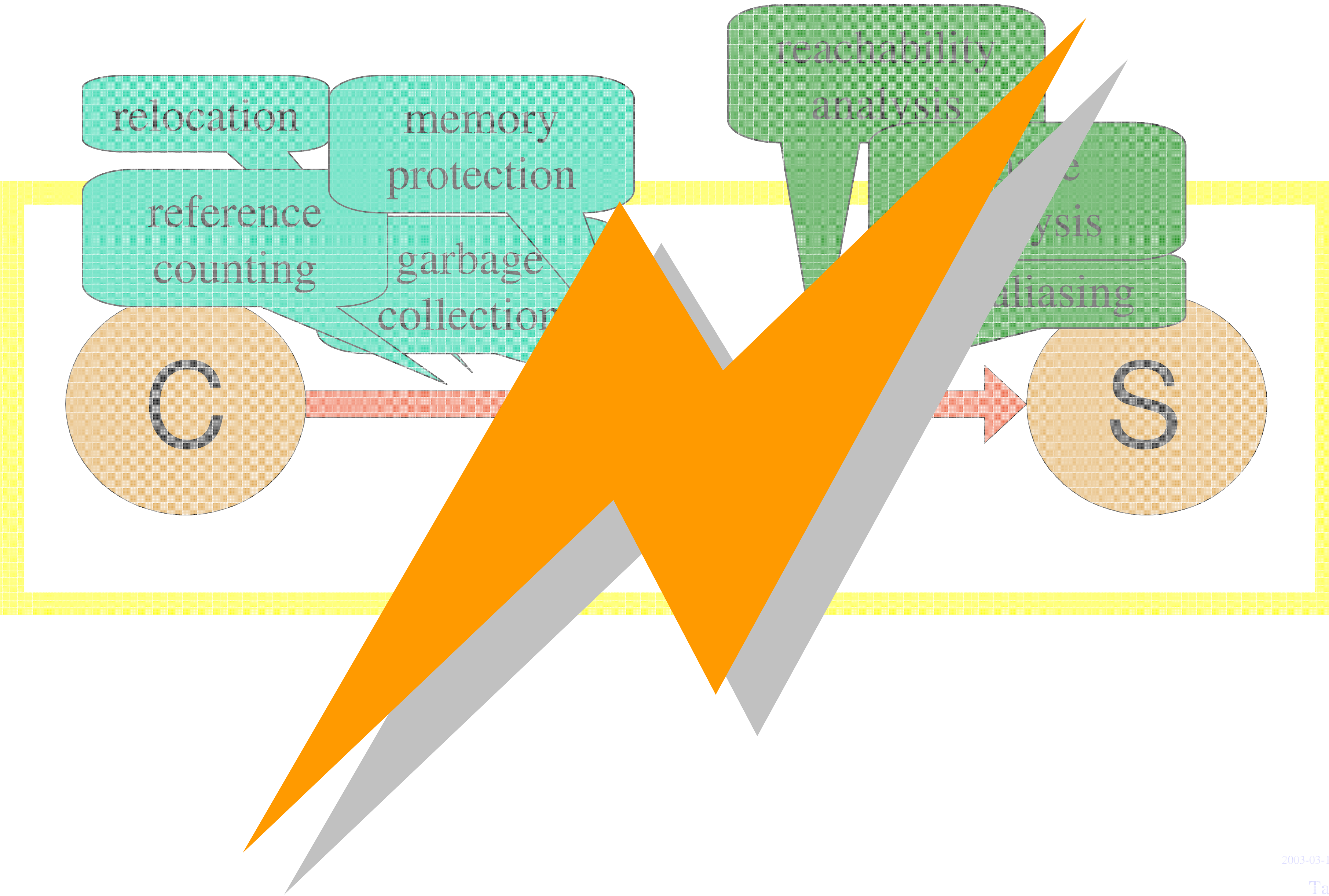
Outline

- Global Communication
  - Why it is different from, e.g., send/receive.
- Global Computation
  - Why it is different from, e.g., method invocation.
- Global Data
  - Why it is different from, e.g., arrays and records.

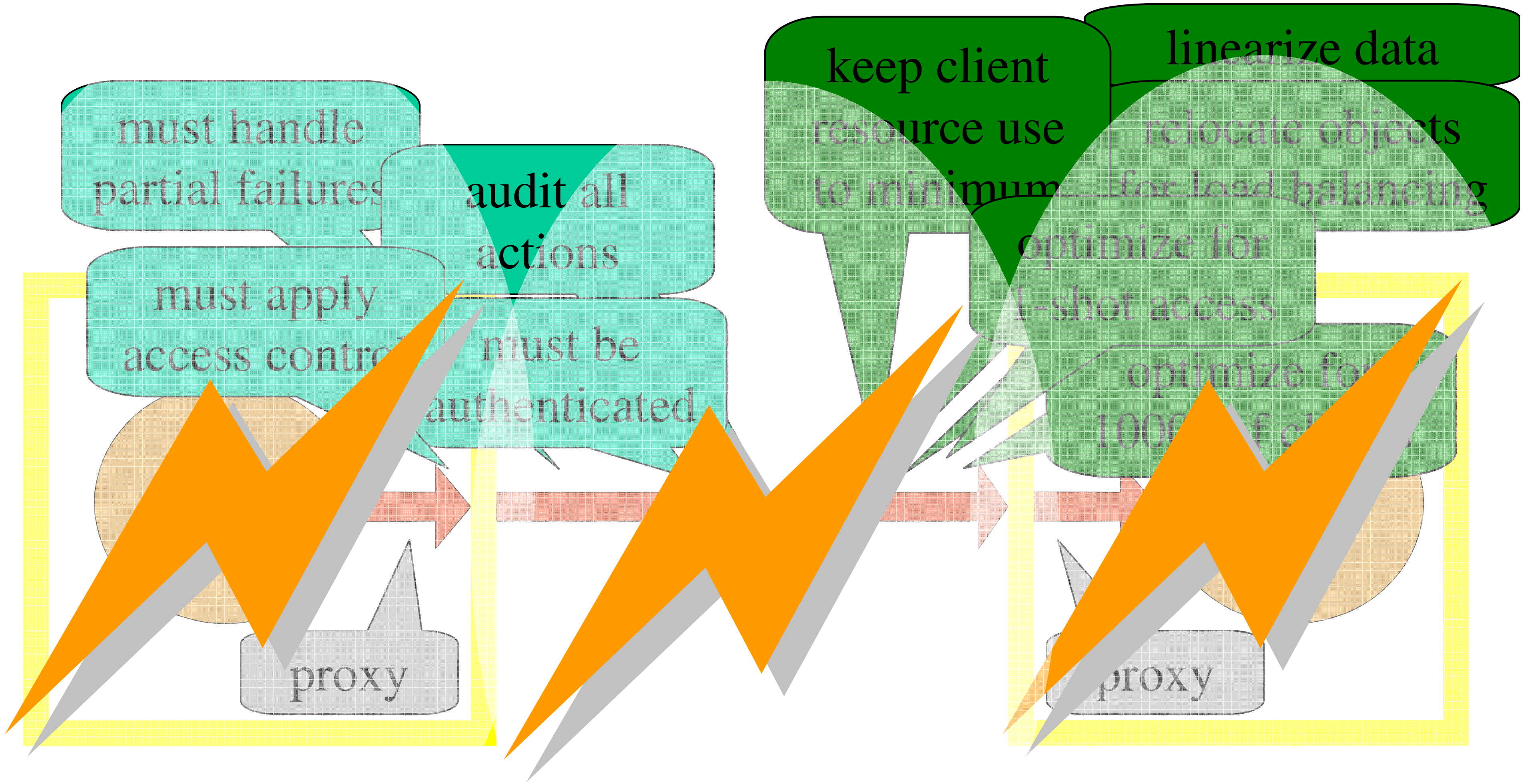
1. Global Communication

- Three "Paradoxes":
  - Wires are very, very complicated.
    Most of Computer Science is about implementing wires.
  - Even when nothing breaks,
    still, things don't work.
  - Having the capability to communicate does not mean being able to communicate.

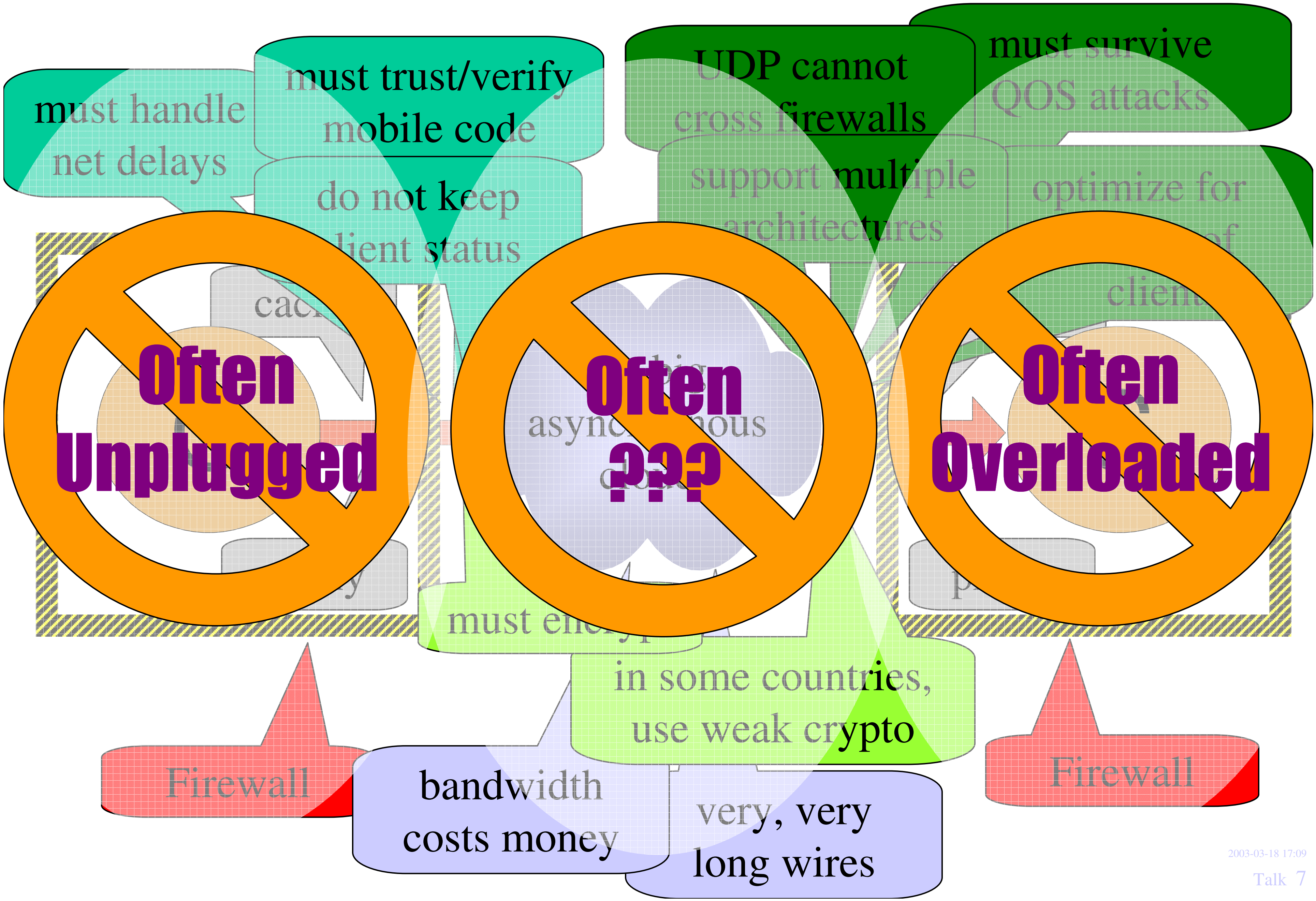
In-Memory Wires



LAN Wires

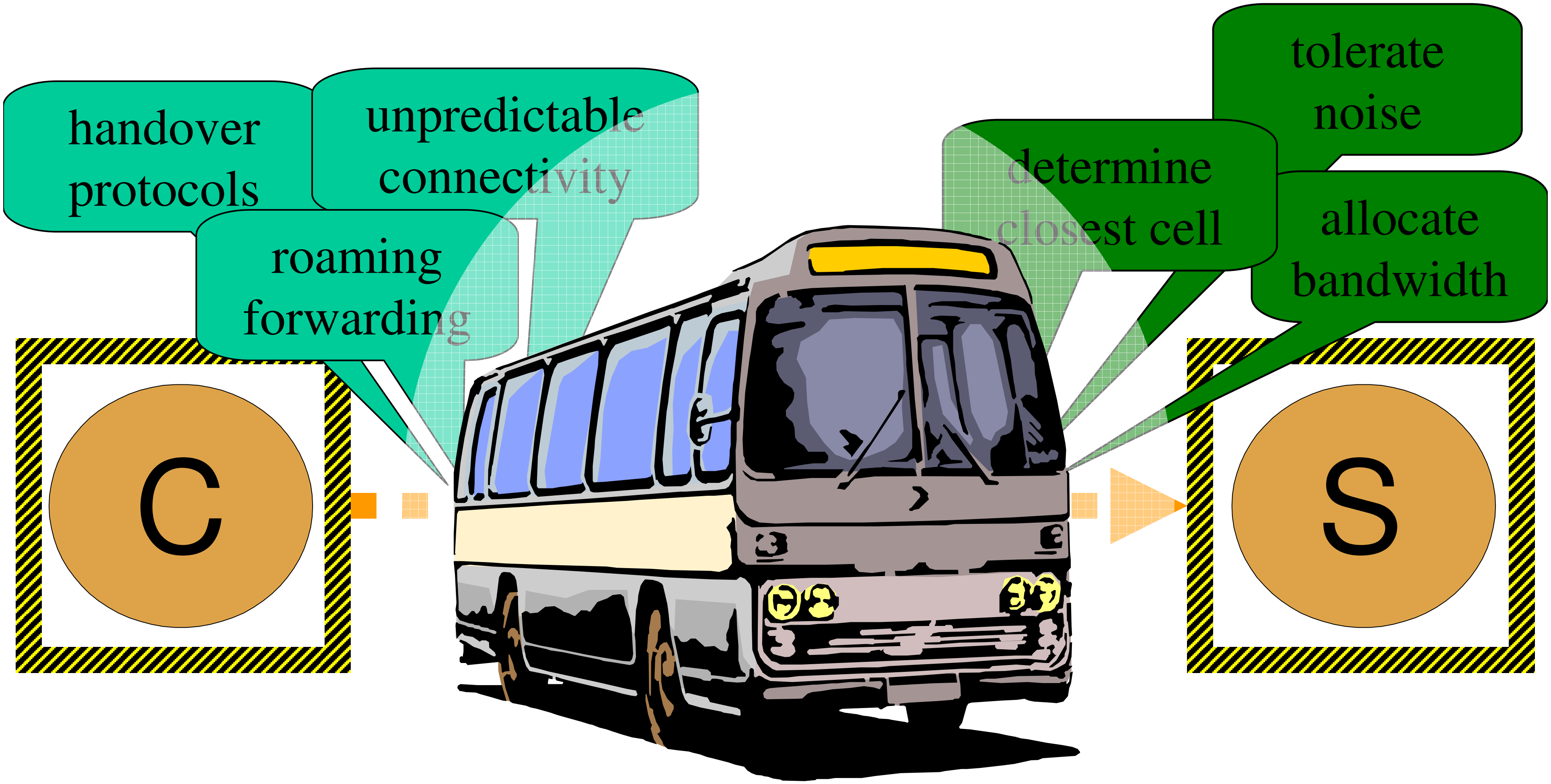

must handle partial failures
must apply access control
audit all actions
must be authenticated
keep client resource use to minimum
linearize data
relocate objects for load balancing
optimize for 1-shot access
proxy
proxy

WAN Wires



must handle net delays
must trust/verify mobile code
do not keep client status
UDP cannot cross firewalls
must survive QOS attacks
support multiple architectures
Often Unplugged
Often ???
Often Overloaded
in some countries, use weak crypto
Firewall
bandwidth costs money
very, very long wires
Firewall

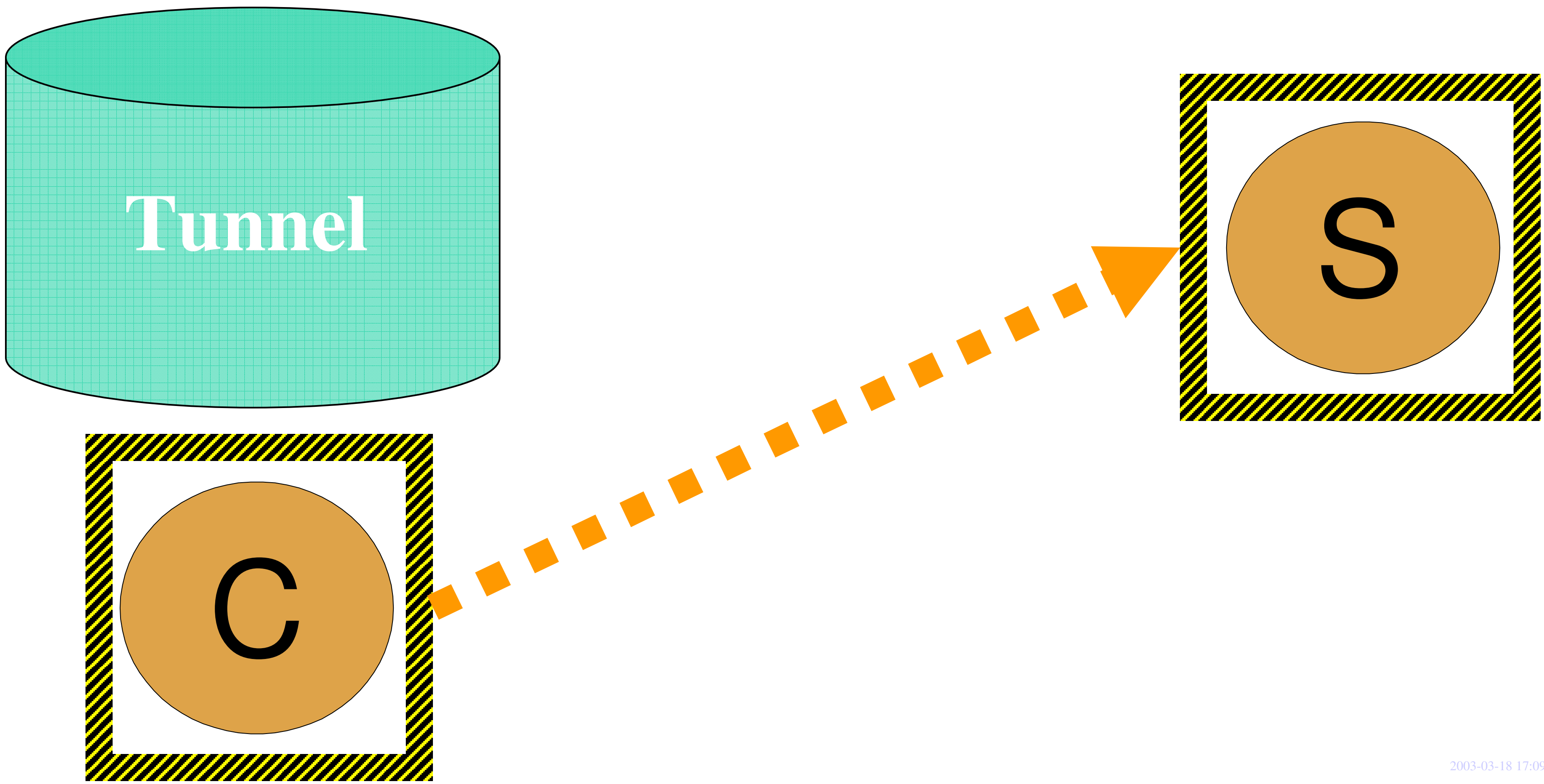
Mobile ("Wireless") Wires



Mobile obstacles

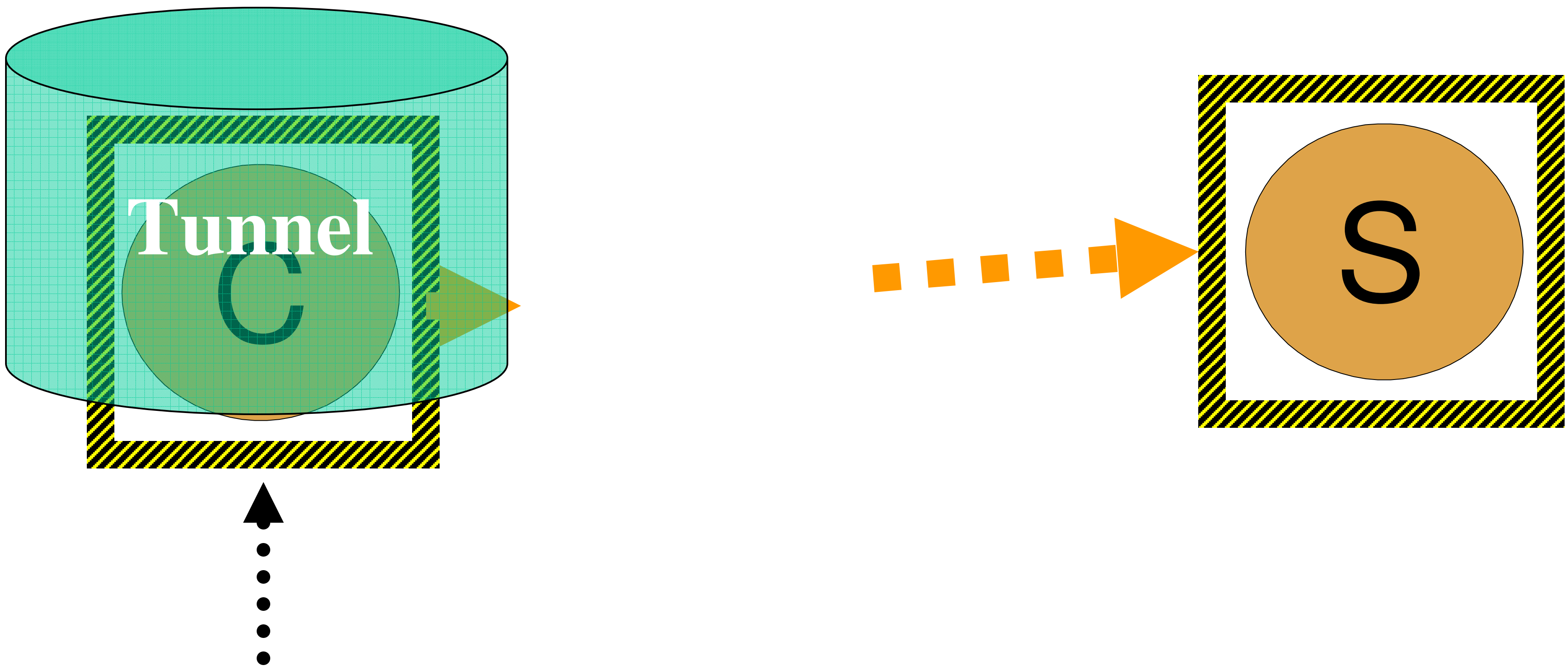
Tunnel Effect

Mobile devices
going around obstacles

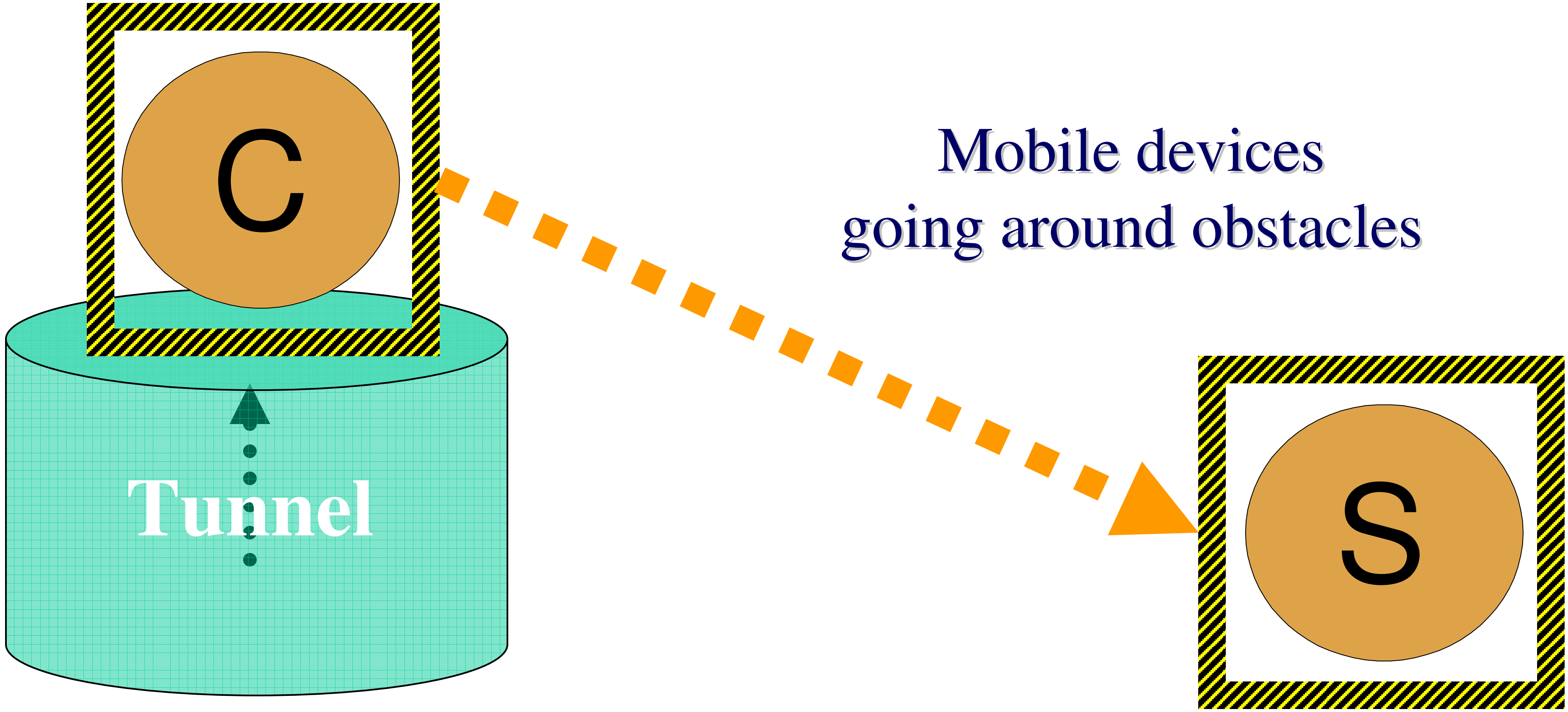


Tunnel Effect

Mobile devices
going around obstacles



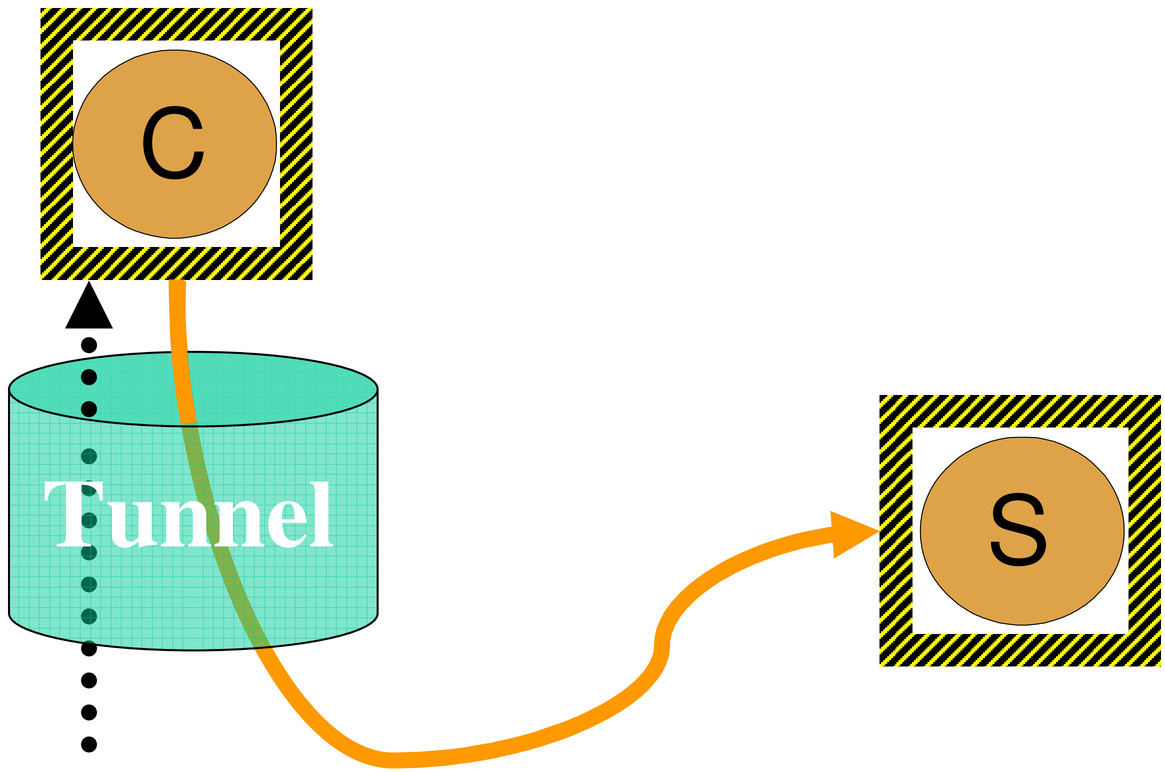
Tunnel Effect



Mobile devices
going around obstacles

Tunnels vs Reliable Communication

- Reliable communication = continuous unbreakable wires



- Reliable communication + Tunnels
  = wires get tangled (and untangling them is hard)
  = eventually one can no longer move (or the wire breaks).

About the Tunnel Effect

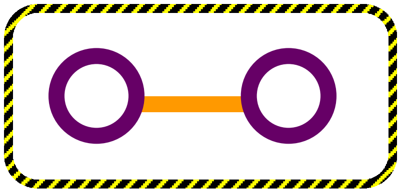
- In hardwired communication:
  - Whoever is *capable* of communication (holds one end of the wire) is always *able* to communicate (send/receive on the wire).
  - Unless, of course, something is broken.
- In the tunnel effect:
  - The client is *capable* of communication (holds one end of the "wire") but is still *unable* to communicate in some cases.
  - Moreover, nothing is broken:
    - The client is working. The server is working.
    - The tunnel tunnels.
    - The ether works like physics says it should.
    - All goes back to normal without need to *fix* anything.
- Just one of a variety of phenomena where…

Sudden Inability to Communicate

- **No longer to be regarded as a failure**
  It is a state of affairs, due to many causes:
  - Congestion (“The server could not be reached.”)
  - Obstructions (“Infrared device out of range.”)
  - Geography (“No Cellnet service in Kinloch Rannoch.”)
  - Security (“No UPS pickup in Area 51.”)
  - Policy (“No mobile phones allowed at Harrod’s.”)
  - Privacy (“Don’t bother me now.”)
  - Psyche (“I left my wireless PDA in my other pants.”)
  - Crime (“My laptop was stolen at Charles De Gaulle’s.”)
  - Physics (“Please wait 8 minutes for answer from Mars.”)
- **Nothing is broken**
  - “broken” ≜ “somebody can be found to fix the problem”.
  - In the cases above, nothing is “broken”. Yet, things don’t work.
  - The failure model is not “it crashed” but “it’s in the wrong place”.

Connectivity Depends on Location

- Proximity:



Ok. Fast (bounded delay), reliable, secure.

- Physical distance:

No such thing as remote real-time control. No unbreakable links.

- Virtual distance:

No such thing as implicitly secure remote links.

Summary: Global Communication

- Mobility is about:
  - Not only mobility of wire endpoints in simple topology (π-calculus, distributed object systems)
  - But also mobility of wire endpoints in complex topology (Ambient Calculus, agent systems).
  - In complex topology, wires endpoints cannot be continuously connected.
- To model global (wide-area, mobile) communication:
  - We need to model *locations* where communication is attempted.
  - We need to make the *capability to communicate* independent from the *ability to communicate*.
  - Capability without ability: security by location access control.
  - Ability without capability: security by resource access control.

2. Global Computation

- How do we embed the features and restrictions of global communication in a computational model?
- We must abandon the familiar notion of function call/handshake.
  - We cannot afford to have every function call over the network to block waiting for an answer. (π vs. async-π.)
- We must even abandon the familiar notion of symmetric multi-party (even async) channel communication.
  - We cannot afford to solve consensus problems all the time. (async-π vs. join.)
- We must abandon the familiar notion of pointers/references.
  - We cannot afford references of any kind that are *always* connected to their target, and we must be able to reconnect them later. (π vs. ambients.)
- We must abandon familiar failure models.
  - We cannot assume that every failure leads to an exception.
  - We cannot assume we are even allowed to know that a failure ever happened.

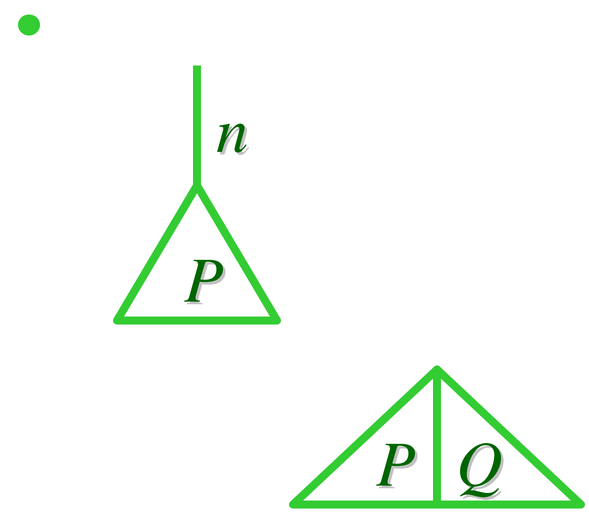
The Ambient Calculus

- The *Ambient Calculus*: a computational model for:
  - Behaviors that are *capable* but sometimes *unable* to communicate.
  - Communication that is neither *broken* nor *not broken*.
- To this end, spatial structures (agents, networks, etc.) are represented by nested locations:

Processes

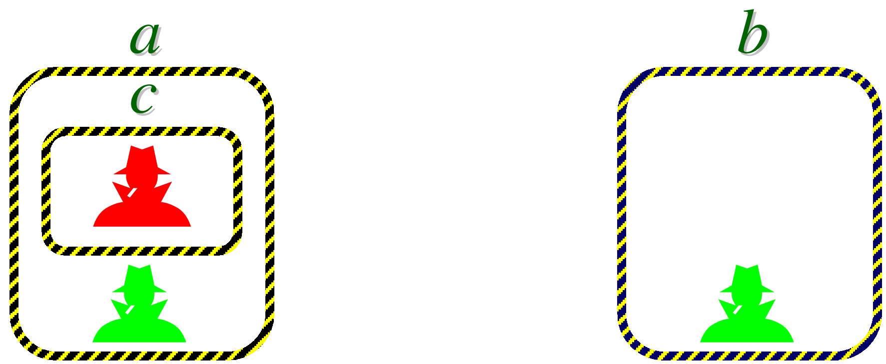
$\mathbf{0}$	(void)
$n[P]$	(location)
$P \mid Q$	(composition)

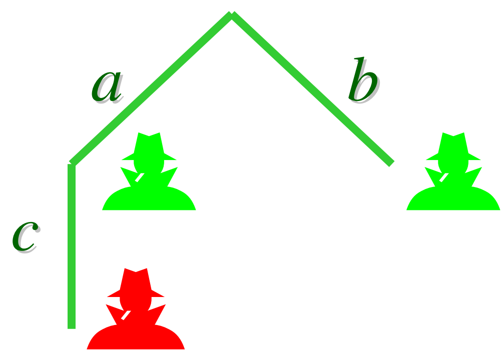
Tree Representation



Mobility

- *Mobility* is change of spatial structures over time.





$a[Q \mid c[out\ a.\ in\ b.\ P]] \qquad \mid b[R]$

Mobility

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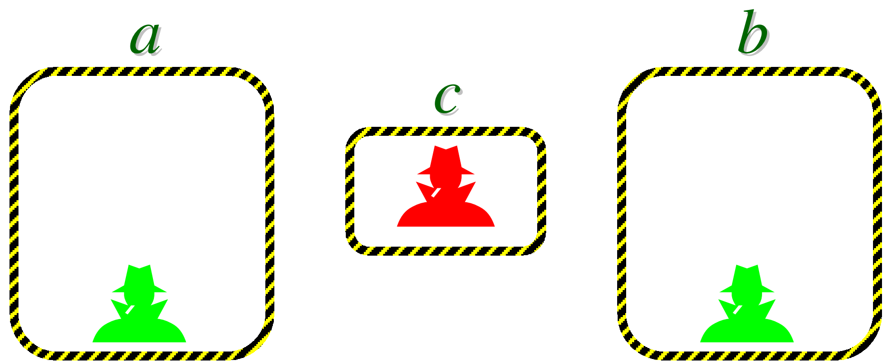

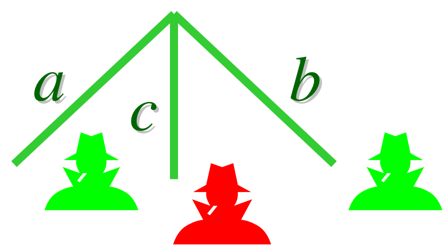

$$a[Q] \mid c[\mathit{in}\ b.\ P] \mid b[R]$$

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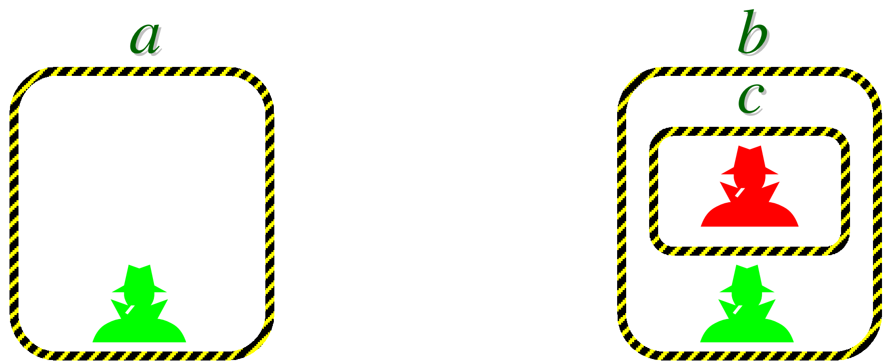
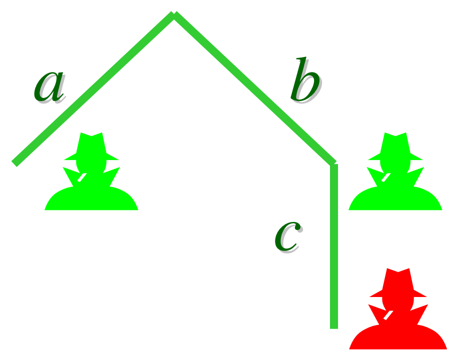
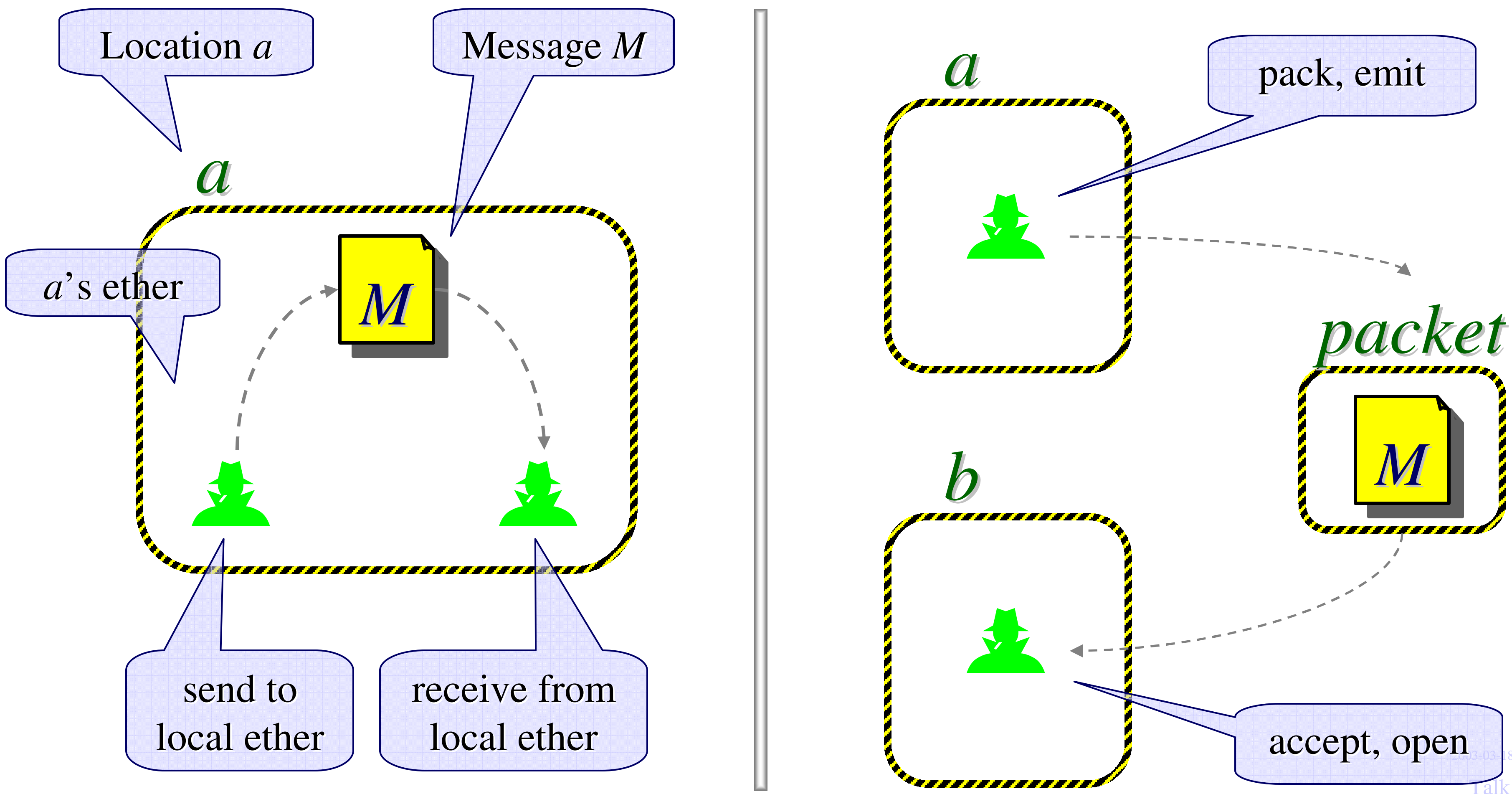




$a[Q] \quad | \; b[R \mid c[P]]$

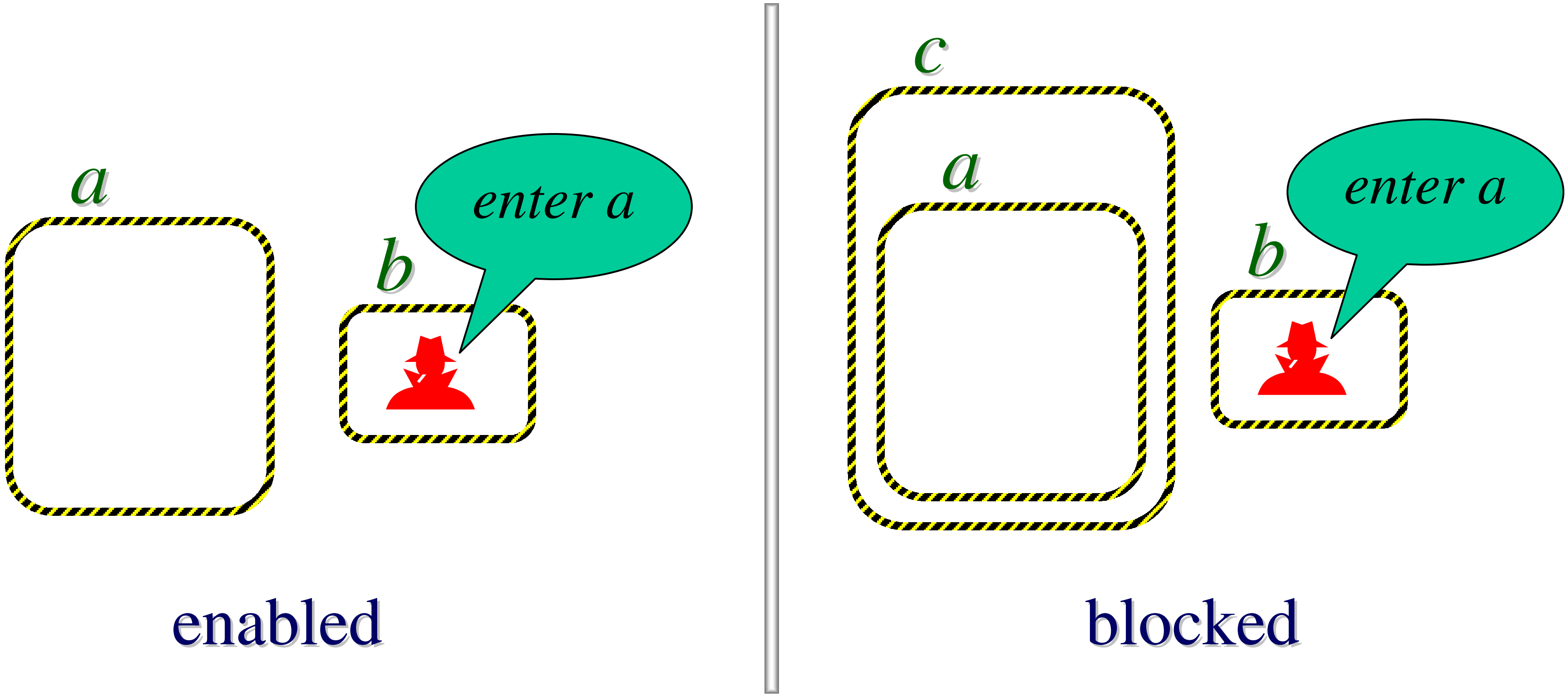
Communication

- Communication is strictly local, within a given location.
- Remote communication must be simulated by sending around mobile packets (which may get lost).



Security

- Security issues are reduced to the capability to create, destroy, enter and exit locations.
  - π-calculus restriction accounts for private capabilities.
  - As for communication, capabilities can be exercised only the the right places.



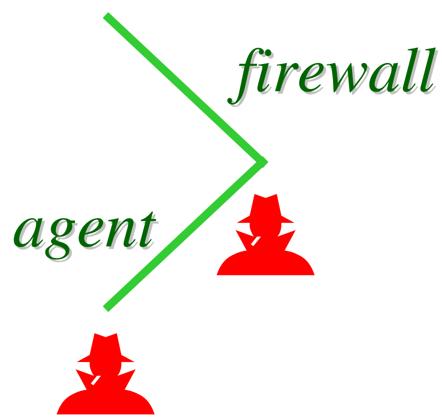
Properties of Global Computation

- In addition to describing global computations, we want to specify their properties.
- These often have the form:
  - Right now, we have a spatial configuration, and later, we have another spatial configuration.
  - E.g.: Right now, the agent is outside the firewall, …

Now

Properties of Global Computation

- In addition to describing global computations, we want to specify their properties.
- These often have the form:
  - Right now, we have a spatial configuration, and later, we have another spatial configuration.
  - E.g.: Right now, the agent is outside the firewall, and later (after running an authentication protocol), the agent is inside the firewall.



Later

A Modal Specification Logic

- In a modal logic, the truth of a formula is relative to a state (called a *world*).
  - Temporal logic: current time.
  - Program logic: current store contents.
  - Epistemic logic: current knowledge. Etc.
- In our case, the truth of a *space-time modal formula* is relative to the *here and now* of a process.
  - The formula $n[\mathbf{0}]$ is read:

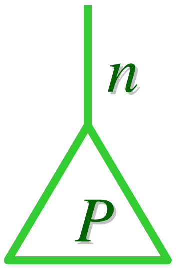
    there is *here and now* an empty location called n
  - The operator $n[\mathcal{A}]$ is a single step in space (akin to the temporal next), so we can talk about that place one step down into n.
  - Other modal operators talk about undetermined times (in the future) and undetermined places (in the location tree).

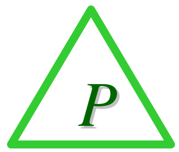
Logical Formulas

$\mathcal{A} \in \Phi ::=$	Formulas	(η is a name n or a variable x)	
$\mathbf{T}$	true		
$\neg\mathcal{A}$	negation		
$\mathcal{A} \vee \mathcal{A}'$	disjunction		
$\mathbf{0}$	void		
$\eta[\mathcal{A}]$	location	$\mathcal{A}@\eta$	location adjunct
$\mathcal{A} \mid \mathcal{A}'$	composition	$\mathcal{A} \triangleright \mathcal{A}'$	composition adjunct
$\eta \circledR \mathcal{A}$	revelation	$\mathcal{A} \oslash \eta$	revelation adjunct
$\diamond\mathcal{A}$	somewhere modality		
$\Diamond\mathcal{A}$	sometime modality		
$\forall x.\mathcal{A}$	universal quantification over names		

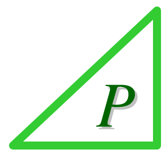
Satisfaction for Basic Operators

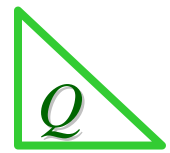
- $\models \mathbf{0}$



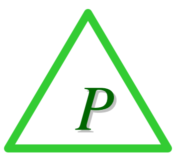
$\models n[\mathcal{A}]$ if


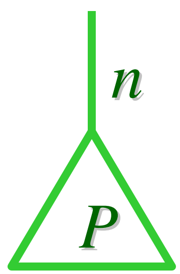
$\models \mathcal{A}$

$\models \mathcal{A} \mid \mathcal{B}$ if


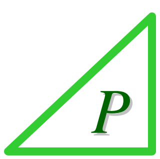
$\models \mathcal{A}$ and


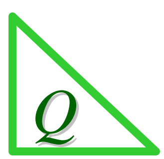
$\models \mathcal{B}$



$\models \mathcal{A}@n$ if


$\models \mathcal{A}$

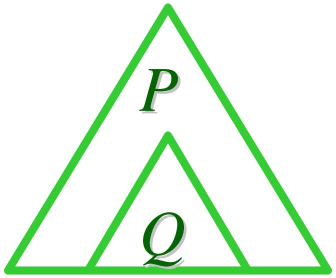


$\models \mathcal{A} \triangleright \mathcal{B}$ if for all


$\models \mathcal{A}$ we have

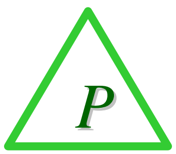

$\models \mathcal{B}$

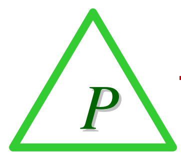
Satisfaction for Somewhere/Sometime



$\models$ ✧$\mathcal{A}$ if 

$\models \mathcal{A}$



$\models \Diamond\mathcal{A}$ if 

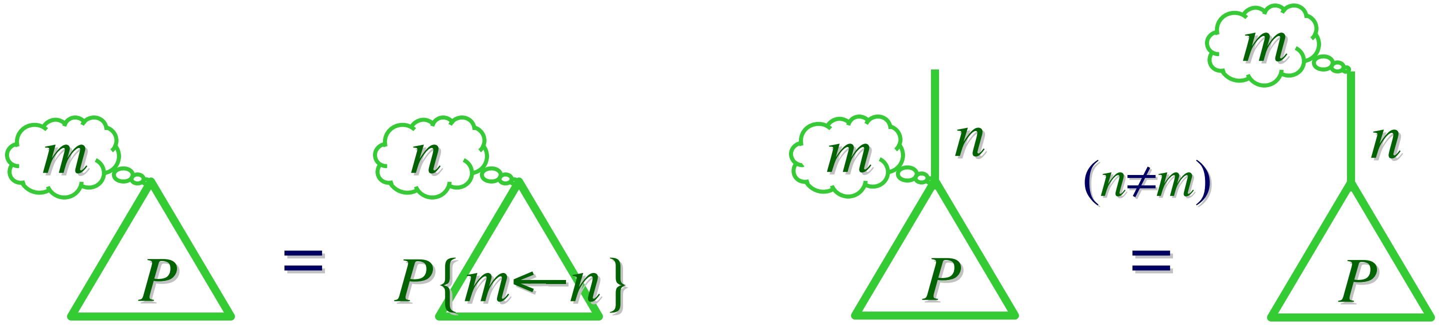
$\longrightarrow^*$ 

and 

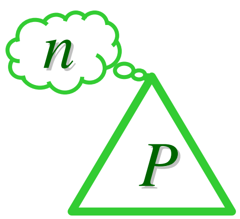
$\models \mathcal{A}$

N.B.: instead of $\Diamond\mathcal{A}$ and ✧$\mathcal{A}$ we can use a “temporal next” operator $\circ\mathcal{A}$, along with the existing “spatial next” operator $n[\mathcal{A}]$, together with μ-calculus style recursive formulas.

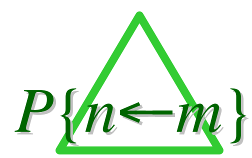
Satisfaction for Hidden and Public Names



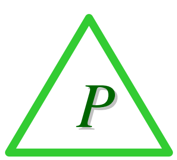
Etc.



$\vDash \mathsf{H}x.\mathcal{A}$ if $\exists m \notin fn(P,\mathcal{A})$



$\vDash \mathcal{A}\{x\leftarrow m\}$



$\vDash$ ©n if $n \in fn(P)$

(Technically, $\mathsf{H}x.\mathcal{A}$ and ©n are defined from n®$\mathcal{A}$ and a Gabbay-Pitts axiom.)

Example: "Shared Secret" Postcondition

- Consider a situation where "a hidden name x is shared by two locations n and m, and is <u>not known</u> outside those locations".

$$\text{H}x.(n[©x] \mid m[©x])$$

  - $P \vDash \text{H}x.(n[©x] \mid m[©x])$

    $\Leftrightarrow \exists r \in \Lambda.\ r \notin fn(P) \cup \{n,m\} \wedge \exists R', R'' \in \Pi.\ P \equiv (\nu r)(n[R'] \mid m[R''])$
    $\wedge\ r \in fn(R') \wedge r \in fn(R'')$

  - E.g.: take $P = (\nu p)\ (n[p[]] \mid m[p[]])$.

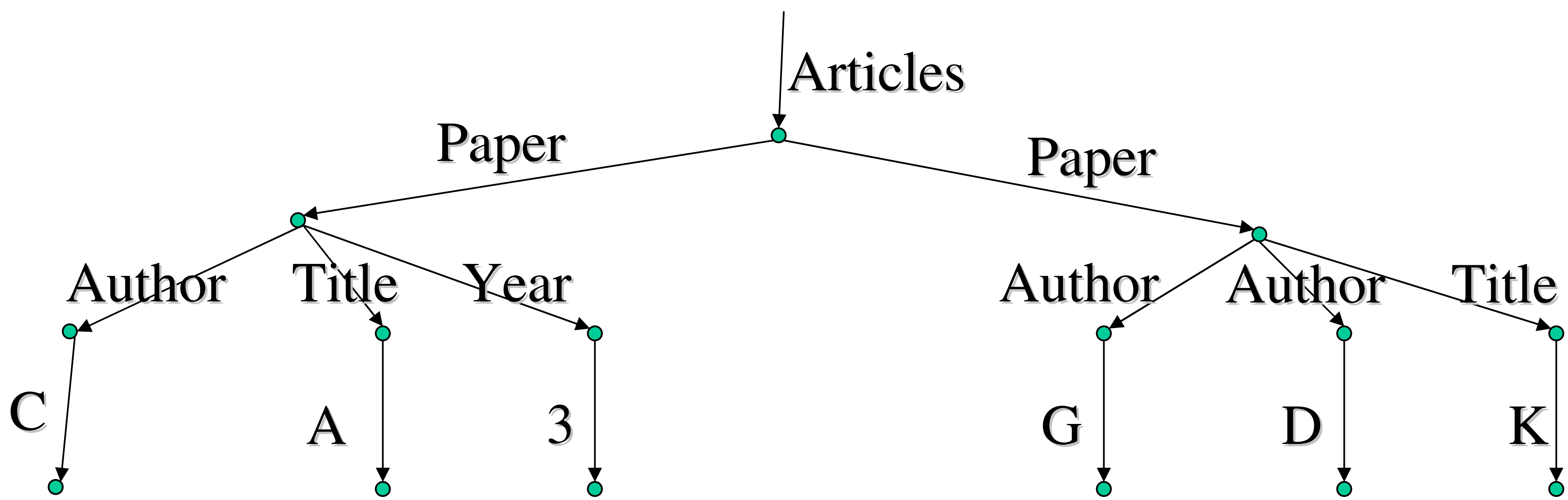
Possible Applications

- Verifying security+mobility protocols.
- Modelchecking security+mobility assertions:
  - If P is $!$-free and $\mathscr{A}$ is $\triangleright$-free, then $P \models \mathscr{A}$ is decidable. (PSPACE-complete [Cheratonik et al. '01].)
  - This provides a way of mechanically checking (certain) assertions about (certain) mobile processes.
- Expressing mobility/security policies of host sites.
  - Conferring more flexibility than just sandboxing the agent.
- Just-in-time verification of code containing mobility instructions
  - By either modelchecking or proof-carrying code.

3. Global Data

- Semistructured Data (a.k.a. XML)

  (Abiteboul, Buneman, Suciu: “Data on the Web” Morgan Kaufman’00.)



Unusual Data

- Not really arrays/lists:
  - Many children with the same label, instead of indexed children.
  - Mixture of repeated and non repeated labels under a node.
- Not really records:
  - Many children with the same label.
  - Missing/additional fields with no tagging information.
- Not really variants:
  - Labeled but untagged unions.
- New “flexible” type theories are required.
  - Based on the “effects” of processes over trees (Ambient Types).
  - Based on tree automata (Xduce).
- Unusual data.
  - Yet, it aims to be the new universal standard for interoperability of programming languages, databases, e-commerce...

Analogies

- An accidental(?) similarity between two areas:
- Semistructured Data is the way it is because:
  - *"Cannot rely on uniform structure"* of data.
    Abandon schemas based on records and disjoint unions.
  - Adopt "self-describing" data structures:
    Edge-labeled trees (or graphs).
- Mobile Computation is the way it is because:
  - *"Cannot rely on static structure"* of networks.
    Abandon type systems based on records and disjoint unions.
  - Adopt "self-describing" network structures:
    Edge-labeled trees (or graphs) of locations and agents.
- Both arose out of the Web, because things there are just too dynamic for traditional notions of data and computation.

Implications

- Immediate implication: a new, uniform, model of data and computation on the Web, with opportunities for cross-fertilization:
  - Programming technology can be used to typecheck, navigate, and transform both dynamic network structures and the semistructured data they contain. Uniformly.
  - Database technology can be used to search through both dynamic network structures (“resource discovery”), and the semistructured data they contain. Uniformly.
- This is still a dream, but it did motivate us to apply a particular technology developed for mobile computation to semistructured data:
  - Specification Logic ➔ Query Logic

A Query Language for Semistructured Data

- *Information trees* $I \in \mathcal{FT}$ (semistructured data)
- *Information terms* F (denoting information trees)
- *Formulas* $\mathcal{A}$ (denoting sets of information trees)
- A semantics of terms $[\![F]\!] \in \mathcal{FT}$
- A semantics of formulas $[\![\mathcal{A}]\!] \subseteq \mathcal{FT}$
- A satisfaction (i.e. matching) relation $F \vDash \mathcal{A}$ (i.e. $[\![F]\!] \in [\![\mathcal{A}]\!]$)
- A *query language* Q (including *from* $F \vDash \mathcal{A}$ *select* Q')
- A (naïve/reference) query semantics $[\![Q]\!] \in \mathcal{FT}$
- A *table algebra* for matching evaluation (i.e. for $F \vDash \mathcal{A}$)
- A (refined) query semantics / query evaluation procedure for Q, based on the table algebra. Correct w.r.t. $[\![Q]\!]$.

The Query Logic

$\mathcal{A}, \mathcal{B} \in \Phi$ ::=	Formulas	(η is a name n or a variable x)
$\mathbf{T}$	true	
$\neg\mathcal{A}$	negation	
$\mathcal{A} \wedge \mathcal{B}$	conjunction	
$\exists x.\mathcal{A}$	existential quantification over label variables	
$\eta \sim \eta'$	label comparison	
$\mathbf{0}$	root	
$\eta[\mathcal{A}]$	edge	
$\mathcal{A} \mid \mathcal{B}$	composition	
X	tree variable	
$\exists X.\mathcal{A}$	existential quantification over tree variables	
ξ	recursion variable	
$\mu\xi.\mathcal{A}$	recursive formula (least fixpoint) ξ may occur only *positively* in $\mathcal{A}$	

Example: Schemas

- A logic is a “very rich type system”. Hence we can comfortably represent various kinds of schemas.
  - However, extensions (or unpleasant encodings) are required for ordered data: $\mathcal{A} \mid \mathcal{B}$ vs. $\mathcal{A} ; \mathcal{B}$.
- Ex.: Xduce-like schemas:

$\mathbf{0}$	the empty tree	
$\mathcal{A} \mid \mathcal{B}$	an $\mathcal{A}$ next to a $\mathcal{B}$	
$\mathcal{A} \vee \mathcal{B}$	either an $\mathcal{A}$ or a $\mathcal{B}$	
$n[\mathcal{A}]$	an edge n leading to an $\mathcal{A}$	
$\mathcal{A}^*$	$\triangleq \mu\xi.\mathbf{0} \vee (\mathcal{A} \mid \xi)$	the merge of zero or more $\mathcal{A}$s
$\mathcal{A}^+$	$\triangleq \mathcal{A} \mid \mathcal{A}^*$	the merge of one or more $\mathcal{A}$s
$\mathcal{A}^?$	$\triangleq \mathbf{0} \vee \mathcal{A}$	zero or one $\mathcal{A}$

Example: Search

- Search:
  - "Find one of my articles (ignore non-articles); bind to *X* all info under the *article* label":

$$S \;=\; \exists X.\ \mathit{article}[(\mathit{author}[\mathit{Cardelli}[\mathbf{0}]] \mid \mathbf{T}) \wedge X] \mid \mathbf{T}$$

  - Can use recursive formulas to search deeper:

$$\mu\xi.\ S \vee \exists x.\ (x[\xi] \mid \mathbf{T})$$

- Not a query language yet.
  - It searches for one instance, not all instances.
  - Some *collecting* primitive must be added. This is going to be based on the logical notion of *satisfaction*.

The Query Language

$\mathcal{Q}$ ::=	Query
from $\mathcal{Q} \vDash \mathcal{A}$ *select* $\mathcal{Q}'$	match and collect
X	matching variable
0	empty result
$\eta[\mathcal{Q}]$	nesting of result
$\mathcal{Q} \mid \mathcal{Q}'$	composition of results
$f(\mathcal{Q})$	tree functions (for extensibility)

- *from* $\mathcal{Q} \vDash \mathcal{A}$ *select* $\mathcal{Q}'$

  All the matches of $\mathcal{Q}$ with $\mathcal{A}$ are computed, producing bindings for the x and X variables that are free in $\mathcal{A}$. The result expression $\mathcal{Q}'$ is evaluated for each (distinct!) such binding, and all the results are merged by $\mid$.
- N.B.: This general approach to building a query language $\mathcal{Q}$ for a logic $\mathcal{A}$, is fairly independent from the details of the logic.

Query Examples

- Joins

$.n[\mathcal{A}] \triangleq n[\mathcal{A}] \mid \mathbf{T}$

Merge info about persons from two db's:

$^{\lambda}$: binding occurrence

from db1 $\vDash$ *.person*[*name*[X^{λ}] | Y^{λ}] *select*
from db2 $\vDash$ *.person*[*name*[X] | Z^{λ}] *select*
person[*name*[X] | Y | Z]

- Restructuring

Rearrange publications from by-article to by-year,
for each distinct year (i.e., for each distinct binding of X):

from db $\vDash$ *.article*[*.year*[X^{λ}]] *select*
publications-by-year[
    year[X] |
    from db $\vDash$ *.article*[*year*[X] | Z^{λ}] *select article*[Z]]

Z binds all fields except *year*; this is rather unusual in QL's

4. Summary

- Global Communication
  - Broadens communication mechanisms.
  - But also restricts the ways in which we can communicate.

    "Connected anytime anywhere to anything." NOT!

- Global Data
  - Relaxes the traditional structure of data.
  - But also restricts what we can assume about it.

    "It's just XML." NOT!

- Global Computation
  - Extends and connects all computational resources.
  - But must deal with new notions of data and communication.

    "I'll just write a script to manage my virtual program committee meeting." NOT!
  - New opportunities: data structures and network structures "look the same".

Conclusions

- Global problems
  - New challenge for most aspects of computation.
- Which require global solutions
  - Uniform solutions hard to implement (“*reboot the internet*”).
  - Federated solutions more likely.
  - Everybody must be able to connect to everybody.
  - Everybody must be able exchange data.
  - Everybody must be able to invoke everybody’s programs.
- Challenges for the present and future
  - Build the infrastucture(s), both practical and theoretical, that will make all this easy.

The End

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