Type-disciplined, Scalable, Practical Composition of Networked Services

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Joint work with
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(and maybe some of you ☺)

The iBench Initiative

CHURCH PROJECT

NRG, BU CS Department

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Alternative titles/subtitles…

- Everything you wanted to know about iBench and were afraid/embarrassed to ask!
- How to (and why sometimes we have to) judge a book by its cover?
- What do you get when you cross network calculus with a type inference engine?
- What computer science problems are worthy of solving in networking?
- Could type theory research be of value to anything other than programming systems?

My agenda is *not*

- To give a 60-minute refresher course in formal type theory and inference
  upon which most of the formalism depends
  - *OK, you'll get some of that…*
- To give a 60-minute crash course in the Network Calculus
  upon which we mostly demonstrate our approach here
  - *OK, you'll get some of that too…*

My agenda is …

- To note the difficulty of analyzing large, complex networks using most existing approaches to compositional analysis
- To propose a type-theory-inspired framework within which to explore ways of scaling up compositional analysis

Compositional analysis

- It's good to know that a network agent (e.g., router, HTTP proxy, …) doesn't crash, when it's disconnected and idle
- It's better to know it won't crash when connected to (composed with) another agent
- It's even better to know it won't crash when composed with a whole bunch of other agents in some arbitrary configuration!

Compositional analysis

- A few potent examples
  - Network protocols
    - What happens when TCP is "modulated" by another control schemes?
  - Compatibility questions
    - Can a stream bridge two networks with similar QoS "goals" but different "mechanisms"? How about three networks?
    - Will upgrading to HTTP 1.1 break my system? (regression is hell!)
  - Data plane interactions
    - Could I substitute a lossless compressor with a lossy one?
  - Control plane interactions
    - Does AS1's BGP policy compose safely with AS2's? Does AS1+AS2 compose with "the world"?
    - Does my firewall security rules compose safely with my network monitoring infrastructure?

Compositional analysis

- A few potent examples
  - Network protocols
    - What happens when TCP is “modulated” [illegible] another cont[illegible]mes?
  - Compatibility questi[illegible]
    - Can a str[illegible] two ne[illegible]orks [illegible]ith sim[illegible] QoS “goals” [illegible]
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    - D[illegible] AS1’s BGP policy compose safely with AS2’s? Does AS1+AS2 [illegible]ompose with “the world”?
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SCALE

Compositional analysis

- Composition:
  The system Z that results from having X interact with Y
- Analysis:
  Formally derive safety properties of a system W
- Analyzing a composition:
  Derive properties of Z by analyzing the composition of X and Y
- Composing the analysis:
  Derive properties of Z by composing the analysis of X and the analysis of Y

Compositional analysis

- Does compositional analysis scale relative to
  - Representation size? *is it manageable?*
  - Representation legibility? *is a PhD required?*
  - Computational tractability? *is it feasible?*
- Examples of analysis “tools”:
  - Queuing theory: What’s the biggest queuing network you were able to analyze?
  - Scheduling theory: What do you get when you use an EDF scheduler in a VM with a RR VMM dispatcher?
  - Finite state models: Welcome to the poster child of the state-space explosion!

Component model composition

$$[A]\bullet[B]\Rightarrow[A\otimes B]$$

$$[A\otimes B]\bullet[C\otimes D]\Rightarrow[A\otimes B\otimes C\otimes D]$$

$$[A\otimes B\otimes C\otimes D]\bullet[E\otimes F\otimes G\otimes H]\Rightarrow[A\otimes B\otimes C\otimes D\otimes E\otimes F\otimes G\otimes H]$$

… how about an Internet-scale application ??? …

Compositional models that preserve functional details of constituent components are not the way to go

Models vs. Components

Claim:

To scale up analysis, the representation of a composition should be of about the same size as that of its constituent components

Approach:

Make $|A \otimes B| \sim |A| \sim |B| \sim 1$

- Represent a component by its I/O signature – i.e., invariants on its interfaces
- No need to retain details that are not explicitly exposed through I/O – loss of expressiveness
- Compositions effectively “hide” interactions between components not exposed at the interface

Soundness vs. Completeness

- Sacrificing expressiveness for scalability is done so as to preserve soundness …
  - Any theorem that we prove about a composition (e.g., property x holds or not) will be correct
- … but may compromise completeness
  - There may be some correct theorems that we will not be able to prove – the fact we cannot prove a theorem does not mean it is not correct
- The question is how much of a gap there is between theorems we can versus cannot prove

The programming analogy…

- We are able to reason about (and hence scale) compositions of large software artifacts by hiding internals and only thinking about interfaces between modules:
  - ➔ All we care about in a library function with which we compose our code is the "signature" of that function, a.k.a. its "type specification"
- Specifying the type of an object is sufficient to use it, and to reason about what you get when you compose it with other objects
  - ➔ We want something similar for network components

Types

fix λ τ σ

Another way of saying models, definitions, specifications, constraints, invariants, *etc…*

Types as constraints

- Types establish constraints on the set of acceptable inputs and promised outputs
- The details encoded in a type/constraint represent a tradeoff between:
  - Expressiveness — *what are you able to prove?*
  - Feasibility — *can you can prove it?*
  - Scalability — *for what size problem?*

TRAFFIC

Typed
Representation and
Analysis of
Flows
For
Interoperability
Checks

TRAFFIC for network gadgets

- Network gadgets consume/produce inputs/outputs over multiple dimensions:
  - E.g., data plane versus control plane
  - E.g., dimensions in a grid setting, N-S & E-W
- Without loss of generality, assume network gadgets have two dimensions
  - Forward dimension (a.k.a., data flow)
  - Backward dimension (a.k.a., control flow)

TRAFFIC: Types

- Each socket has a type

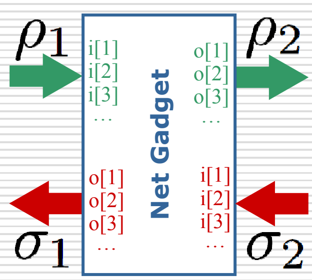
$$\begin{array}{lcll} r & \in & \text{FwSocketType} & \\ s & \in & \text{BwSocketType} & \\ t & \in & \text{SocketType} & ::= \; r \mid s \end{array}$$

- Sockets in a given direction make a bundle of some type

$$\begin{array}{lcll} \rho & \in & \text{FwType} & ::= \; r \mid (\rho_1 \cdot \rho_2) \\ \sigma & \in & \text{BwType} & ::= \; s \mid (\sigma_1 \cdot \sigma_2) \\ \tau & \in & \text{Type} & ::= \; \rho \mid \sigma \end{array}$$

- Two forward and two backward bundles make up a (gadget) flow

$$T \in \text{FlowType} \quad ::= \begin{bmatrix} \rho_1 & \rho_2 \\ \sigma_1 & \sigma_2 \end{bmatrix}$$



TRAFFIC: Types

- Examples of constraints and relationships we want to encode using types
  - A video source is variable-bit-rate with a steady-state rate of r Mbps and a burst magnitude of no more than b Mb.
  - A steady-state AIMD source with loss rate p, a RTT of T, and an MTU M will send at a rate of at most $1.3*M/(\mathrm{sqrt}(p)*T)$
  - A video client is willing to tolerate up to $p\%$ steady-state loss rate and a steady-state delay of less than T seconds.
  - A wireless hop drops at least $p_l\%$ and at most $p_u\%$ packets, plus a single burst of at most b packets at steady-state.
  - A traffic shaper adds less than T secs of delay, smoothing all transmissions to a steady state rate of r Mbps.

TRAFFIC: Type relationships

- Definition: A type t_1 is a subtype of t_2 (denoted t_1 <: t_2) if t_1 is more "constrained" than t_2

$$\frac{\{t_1 <: t_2\} \subseteq \Delta}{\Delta \vdash t_1 <: t_2} \qquad \frac{\tau \in \mathsf{Type}}{\Delta \vdash \tau <: \tau} \qquad \frac{T \in \mathsf{FlowType}}{\Delta \vdash T <: T}$$

- Subtyping rules for bundles and flows

$$\frac{\Delta \vdash r <: r' \qquad \Delta \vdash \rho <: \rho'}{\Delta \vdash r\,\rho <: r'\,\rho'} \qquad \frac{\Delta \vdash \rho_1' <: \rho_1, \Delta \vdash \rho_2 <: \rho_2', \Delta \vdash \sigma_1 <: \sigma_1', \Delta \vdash \sigma_2' <: \sigma_2}{\Delta \vdash \begin{bmatrix} \rho_1 & \rho_2 \\ \sigma_1 & \sigma_2 \end{bmatrix} <: \begin{bmatrix} \rho_1' & \rho_2' \\ \sigma_1' & \sigma_2' \end{bmatrix}}$$

- Subtyping is transitive

$$\frac{\Delta \vdash \tau_1 <: \tau_2 \qquad \Delta \vdash \tau_2 <: \tau_3}{\Delta \vdash \tau_1 <: \tau_3}$$

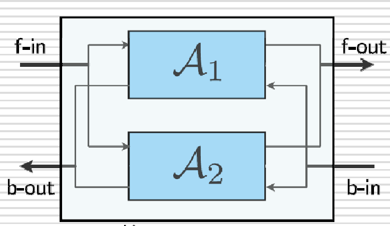
TRAFFIC: Type relationships

- How do we come up with these relationships?
  - Using domain knowledge or specifics related to standards or implementation details
    - TCP window size/rate is bounded by receiver window
    - TCP rate is bounded by TCP equation at steady state
  - By leveraging well-grounded theories and calculi – e.g., queuing, control, scheduling theory, network calculus, …
    - Delay of M/M/1/K is always less than that of M/M/1
    - Error of PI controller is more than that of PID controller
- Using TRAFFIC for compositional analysis depends on the goodness of these relationships!
  - Garbage-In = Garbage-Out

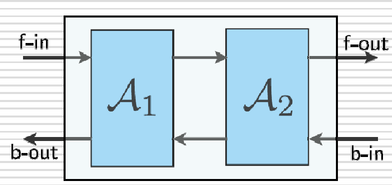
TRAFFIC: Type constructs

- A system is an arrangements of gadgets

$$
\begin{array}{rcllll}
x, y, z & \in & \mathsf{FlowVar} & & & \text{flow variable} \\
A, B, C & \in & \mathsf{LocalFlow} & & & \text{local flow} \\
\mathcal{A}, \mathcal{B}, \mathcal{C} & \in & \mathsf{GlobalFlow} & ::= & A \quad | \quad x & \\
 & & & | & \mathcal{A}; \mathcal{B} & \text{sequential flow} \\
 & & & | & \mathcal{A} \| \mathcal{B} & \text{parallel flow} \\
 & & & | & \textbf{let } x = \mathcal{A} \textbf{ in } \mathcal{B} & \text{let-binding}
\end{array}
$$



$\mathcal{A}_1 \| \mathcal{A}_2$ (parallel)



$\mathcal{A}_1; \mathcal{A}_2$ (sequential)

TRAFFIC: Type inference

- Type of a parallel arrangement of gadgets

$$\frac{\Gamma, \Delta \vdash \mathcal{A} : T \quad \Gamma, \Delta \vdash \mathcal{B} : T'}{\Gamma, \Delta \vdash \mathcal{A} \| \mathcal{B} : T \bullet T'} \quad \textit{where} \begin{bmatrix} \rho_1 & \rho_2 \\ \sigma_1 & \sigma_2 \end{bmatrix} \bullet \begin{bmatrix} \rho_3 & \rho_4 \\ \sigma_3 & \sigma_4 \end{bmatrix} = \begin{bmatrix} \rho_1 \bullet \rho_3 & \rho_2 \bullet \rho_4 \\ \sigma_1 \bullet \sigma_3 & \sigma_2 \bullet \sigma_4 \end{bmatrix}$$

- Type of a sequential arrangement of gadgets

$$\frac{\Gamma, \Delta \vdash \mathcal{A} : \begin{bmatrix} \rho_1 & \rho_2 \\ \sigma_1 & \sigma_2 \end{bmatrix} \quad \Gamma, \Delta \vdash \mathcal{B} : \begin{bmatrix} \rho_3 & \rho_4 \\ \sigma_3 & \sigma_4 \end{bmatrix} \quad \Delta \vdash \rho_2 <: \rho_3 \quad \Delta \vdash \sigma_3 <: \sigma_2}{\Gamma, \Delta \vdash \mathcal{A} ; \mathcal{B} : \begin{bmatrix} \rho_1 & \rho_4 \\ \sigma_1 & \sigma_4 \end{bmatrix}}$$

TRAFFIC: Let bindings

- Flow variables
  - Allow us to represent and reason about unknown entities in the network
  - Examples:
    - HTTP agent is 1.0 or 1.1 compliant
    - TCP agent is Reno or Tahoe
    - Buffer is DropTail or RED
    - …
- Useful as a placeholder for
  - Type Checking:
    - Check all possible types of gadgets with which we may interact
  - Type Inference:
    - Infer the type of gadget to "plug in" for things to work out

TRAFFIC: Type inference

A ; (B || C) ; D ; (E || F || G)

- Fully known network
- Do the pieces "fit"? Are all requirements satisfied?

A ; (*x* || C) ; *y* ; (E || F || G)

- Partially known network
- Do the known pieces "fit"?
- What is required of unknown pieces?

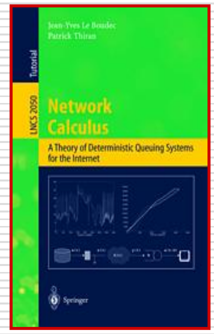
Work Forward: engineer to meet specs
...or Backward: which extant pieces will fit?

TRAFFIC instantiations

- An instantiation of TRAFFIC requires us to define a type system:
  - What are the set of possible types?
  - What sub-typing relationships exist?
  - What type transformation are possible?
- TRAFFIC(Network Calculus):
  - NetCal provides a nice set of possible types
  - NetCal allows derivation of sub-typing rules
  - NetCal enables derivation of type transforms

TRAFFIC over Network Calculus

- What is Network Calculus?
  - NetCal introduced by Jean-Yves Le Boudec & Patrick Thiran; building on the seminal works of Parekh & Gallager (circa mid 1990s)
  - NetCal is a collection of results based on Min-Plus algebra, which applies to deterministic queuing systems found in communication networks
  - Allows us to reason about bounds on capacity, demand, utilization, *etc…* with bounding functions over time intervals

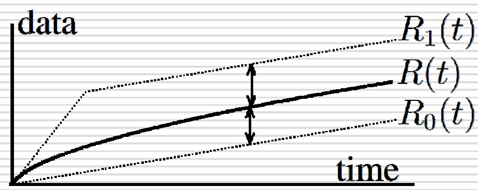


NetCal + TRAFFIC

- We are not making NetCal more powerful
  - On the contrary, analysis "by hand" using NetCal would produce more refined/expressive results than will be possible with TRAFFIC over NetCal
  - Recall that trading off expressiveness for scalability is the stated goal of our approach!
- We are distilling and codifying NetCal so as to use it to mechanically analyze systems in TRAFFIC
  - Type expressions require a working familiarity with NetCal to be intelligible…
  - But, ultimately NetCal will be hidden from the average network programmer or architect, just as the details of data representation are hidden from programmers…

NetCal: Data flow types

- Data Flow $R(t)$
  - Bits seen in [0,t)
  - Rate (dR/dt) is a byproduct; need not be defined!



- One may use data flow functions as "bounds" to define classes of TRAFFIC types for data flows (denoted by "R")
  - Consider the function $f(t) = 0.25t + \sqrt{t}$
    - $\lfloor\!\lfloor 0 \rfloor\!\rfloor_R$ is a clear lower bound ➔ $f(t) : \lfloor\!\lfloor 0 \rfloor\!\rfloor_R$
    - $\lfloor\!\lfloor 0.25t \rfloor\!\rfloor_R$ is another lower bound ➔ $f(t) : \lfloor\!\lfloor 0.25t \rfloor\!\rfloor_R$
    - $\lceil\!\lceil 0.75t + 0.5 \rceil\!\rceil_R$ is an upper bound ➔ $f(t) : \lceil\!\lceil 0.75t + 0.5 \rceil\!\rceil_R$
    - Using intersections of types ➔ $f(t) : \lfloor\!\lfloor 0.25t \rfloor\!\rfloor_R \cap \lceil\!\lceil 0.75t + 0.5 \rceil\!\rceil_R$

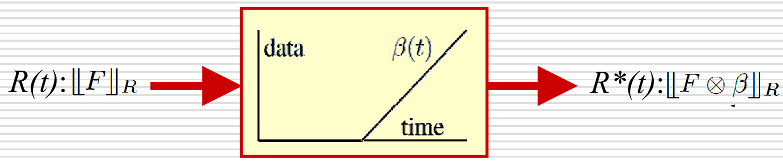
NetCal: Arrival curve types

- Arrival (Process) Curves
  - Bits seen in an interval (a window of time) t
- One may use arrival curves as "bounds" to define classes of TRAFFIC arrival processes (denoted by "α")
  - One can show that for any arrival curve $f(t)$, $\lceil\!\lceil f \rceil\!\rceil_\alpha <: \lceil\!\lceil f \rceil\!\rceil_R$
  - One can show that for any data flow function $f(t)$ and arrival curve $g(t)$, $\lceil\!\lceil f \rceil\!\rceil_R <: \lfloor\!\lfloor g \rfloor\!\rfloor_\alpha$ iff $f(t) - f(s) \leqslant g(t-s)$, for all intervals s and t
    - Thus for the leaky bucket function $\alpha(t) = rt + b$ with steady state rate r and burst size b, we get $\lceil\!\lceil rt+b \rceil\!\rceil_R <: \lfloor\!\lfloor rt+b \rfloor\!\rfloor_\alpha$

NetCal: Service curve types

- Service (Process) Curves
  - How an incoming data flow $R(t)$ is serviced (e.g., delayed and rate limited) to produce an outgoing data flow $R^*(t)$

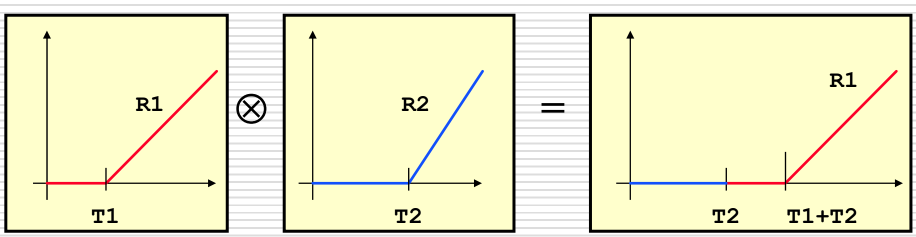
$$R^*(t) \geqslant \min_{s \leqslant t} (R(s) + \beta(t-s))$$



- Ougoing data flow $R^*(t)$ is the convolution using min-plus algebra of incoming flow $R(t)$ and service curve $\beta(t)$

NetCal: On convolution of flows

- Example



Standard convolution:

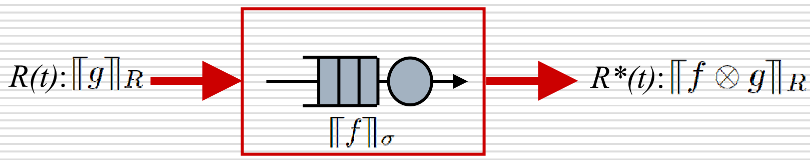
$$(f * g)(t) = \int f(t-u) g(u) du$$

Min-plus convolution:

$$f \otimes g(t) = \min_u \{f(t-u) + g(u)\}$$

NetCal: Shaper curve types

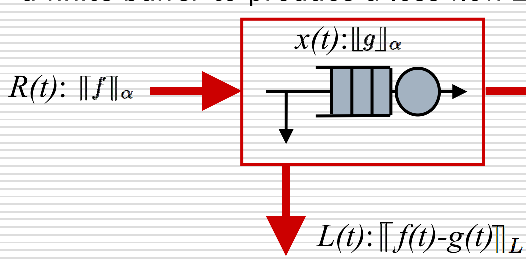
- Shaper Curves
  - How an incoming data flow $R(t)$ is shaped through the use of a (in)finite buffer to produce an outgoing data flow $R^*(t)$



- Outgoing data flow $R^*(t)$ is the convolution using min-plus algebra of incoming flow $g(t)$ and shaper curve $f(t)$

NetCal: Lossy shaper types

- Loss Curves
  - How an incoming data flow $R(t)$ is shaped through the use of a finite buffer to produce a loss flow $L(t)$



- One may use loss "bounds" to define classes of TRAFFIC loss flows (denoted by "L") or loss rates (denoted by "l")
  - A flow with a loss rate of no more than 5 bps would have the type $\llbracket 5t \rrbracket_L$ whereas one with 1% loss would be $\llbracket 0.01 \rrbracket_l$

NetCal: Additional inferences

Incoming	Outgoing
$\lfloor\!\lfloor F \rfloor\!\rfloor_R$	$\lfloor\!\lfloor F \otimes \beta \rfloor\!\rfloor_R$
$\lceil\!\lceil F \rceil\!\rceil_R$	$\lceil\!\lceil G \rceil\!\rceil_\sigma \cap \lceil\!\lceil F \otimes G \rceil\!\rceil_R$
$\lceil\!\lceil F \rceil\!\rceil_R$	$\lfloor\!\lfloor Q \rfloor\!\rfloor_L \cap \lceil\!\lceil F - Q \rceil\!\rceil_R$
$\lfloor\!\lfloor F \rfloor\!\rfloor_R$	$\lceil\!\lceil Q \rceil\!\rceil_L \cap \lfloor\!\lfloor (F - Q) \otimes \beta \rfloor\!\rfloor_R$
$\lceil\!\lceil F \rceil\!\rceil_R$	$\lfloor\!\lfloor Q \rfloor\!\rfloor_L \cap \lceil\!\lceil G \rceil\!\rceil_\sigma \cap \lceil\!\lceil (F - Q) \otimes G \rceil\!\rceil_R$

TRAFFIC: Putting it together

Consider a simple video delivery network

$$\mathit{video1} \,\|\, \mathit{video2}; \mathit{shaper}; \mathit{delivery}; (\mathit{clientA} \,\|\, \mathit{clientB})$$

Where

video nodes Each outgoing socket is $\lfloor\!\lfloor t - 5 \rfloor\!\rfloor_R \cap \lceil\!\lceil t + 5 \rceil\!\rceil_\alpha$

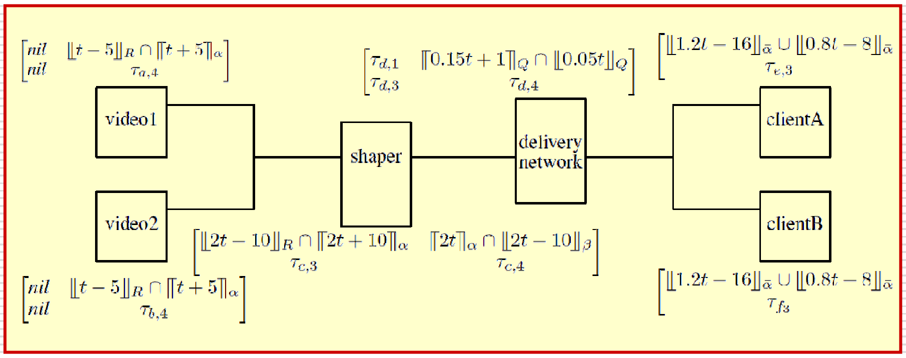
shaper node Incoming socket is $\lfloor\!\lfloor 2t - 10 \rfloor\!\rfloor_R \cap \lceil\!\lceil 2t + 10 \rceil\!\rceil_\alpha$
Service curve is $\lfloor\!\lfloor 2t - 10 \rfloor\!\rfloor_\beta$ shaper is $\lceil\!\lceil 2t \rceil\!\rceil_\sigma$

delivery network Loss rate is $\lceil\!\lceil 0.15t + 1 \rceil\!\rceil \cap \lfloor\!\lfloor 0.05t \rfloor\!\rfloor$

client nodes Each incoming socket is $\lfloor\!\lfloor 1.2t - 16 \rfloor\!\rfloor_{\bar{\alpha}} \cup \lfloor\!\lfloor 0.7t - 4.5 \rfloor\!\rfloor_{\bar{\alpha}}$

Will it work?

TRAFFIC: Putting it together



Note: Backward path is unconstrained

TRAFFIC: Code

```
//   System specification as interconnections of gadgets
specification Spec = begin
 (Video || Video) ; Connector1 ; Shaper ; Delivery ; Connector2 ; (Client || Client)
end


//   Defining components along with their types ([fw-in , fw-out  ;  bw-out , bw-in ])
localflows L: D = begin
  let Video      = ["nil"       , "t1"        ; (0,0) , (0,0)]
  let Connector1 = [("t2"*"t2"), "t3"         ; ((0,0)*(0,0)),(0,0)]
  let Shaper     = ["t4"        , "t5"        ; (0,0), (0,0)]
  let Delivery   = ["top"       , "t6"        ; (0,0), (0,0)]
  let Connector2 = ["t7"        , ("t8"*"t8") ; (0,0), ((0,0)*(0,0))]
  let Client     = ["t9"        , "nil"       ; (0,0), (0,0) ]
end


//   Socket types and subtype relationships obtained using NetCal engine or library:
relations D = begin
  BwSocketType ::= Range  // backward types don't play a role in this example
  FwSocketType ::= "nil" | "top" | "t1" | "t2" | "t3" | "t4" | "t5" | "t6" | "t7" | "t8" | "t9"
  where     // below are the subtype relationships:
     "t1" <: "t2" ;
     "t3" <: "t4" ;
     "t5" <: "top"; // "top" is the supertype of all types.
     "t6" <: "t7" ;
     "t8" <: "t9"
end


//    Check network configuration:
typing T1 = check Spec : D using L
```

TRAFFIC: In action

- Type checker uses NetCal relationships and TRAFFIC rules to check if sub-typing constraints are satisfied
  - System checks if all is well
  - System does not check otherwise
- Let's try it – *thank you Likai & Yarom!*
  - http://cs-people.bu.edu/yarom/ibench/traffic/index.php

TRAFFIC: In action

- What if we have multiple choices – *e.g.,*

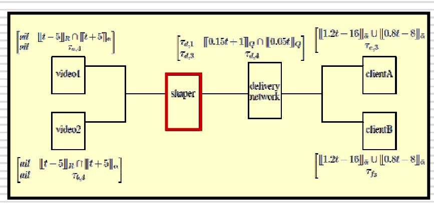
Shaper is

$$\left[\underbrace{\lfloor 2t-10 \rfloor_R \cap \lceil 2t+10 \rceil_\alpha}_{\tau_{c,3}} \quad \underbrace{\lceil 2t \rceil_\alpha \cap \lfloor 2t-10 \rfloor_\beta}_{\tau_{c,4}}\right]$$

or

$$\left[\underbrace{\lfloor 2t-5 \rfloor_R \cap \lceil 2t+10 \rceil_\alpha}_{\tau_{c,3}} \quad \underbrace{\lceil 2t \rceil_\alpha \cap \lfloor 2t-10 \rfloor_\beta}_{\tau_{c,4}}\right]$$

in



- Let's try it
  - http://cs-people.bu.edu/yarom/ibench/traffic/index.php

TRAFFIC: Another example

```
specification LossyVideoDelivery = begin
 let x =  LossyNet in (spec VideoDelivery)
end

specification ReliableVideoDelivery = begin
 let x =  ReliableNet in (spec VideoDelivery)
end

specification VideoDelivery = begin
 Video ; Compress ; x ; Decompress; Client
end

localflows L: D = begin
  let Video       = ["nil"       , "t1"        ; (0,0), (0,0)]
  let Compress    = ["top"       , "t2"        ; (0,0), (0,0)]
  let LossyNet    = ["top"       , "t3a"       ; (0,0), (0,0)]
  let ReliableNet = ["top"       , "t3b"       ; (0,0), (0,0)]
  let Decompress  = ["t4"        , "t5"        ; (0,0), (0,0)]
  let Client      = ["t6"        , "nil"       ; (0,0), (0,0)]
end

relations D = begin
  BwSocketType ::= Range  // backward types don't play a role in this example
  FwSocketType ::= "nil" | "top" | "t1" | "t2" | "t3a" | "t3b" | "t4" | "t5" | "t6"
  where      // below are the subtype relationships:
     "t1"  <: "top" ; "t2" <: "top" ; "t3a" <: "top" ; "t3b" <: "top" ;
     "t4"  <: "top" ; "t5" <: "top" ; "t6" <: "top" ; // top is supertype
     "t2"  <: "t1"  ;  // compressor output data flow is a subtype of its input
     "t3a" <: "t2"  ;  // network is lossy
     "t2"  <: "t3b" ;  // network is reliable
     "t3b" <: "t2"  ;  // network is reliable
     "t2"  <: "t4"  ;  // decompressor input accepts any output of a compressor
     "t5"  <: "t1"  ;  // data flow out of compressor cannot be more than original
     "t1"  <: "t6"  ;  // client input data flow can take the original video output
     "t6"  <: "t1"     // client input data cannot exceed original data
end

typing T1 = check LossyVideoDelivery : D using L
typing T2 = check ReliableVideoDelivery : D using L
```


TRAFFIC: What’s next?

- Write TRAFFIC specs for a host of network gadgets and compositions
- Develop a NetCal oracle to find out if type A is a subtype of type B, using min-plus algebra
- Leverage other theories, e.g., scheduling theory, to develop other oracles
- Add TRAFFIC checking/inference to a network programming environment, e.g., snBench
- Make it transparent to users/programmers, e.g., develop GUI, couple with **ns**, …
- Allow for more expressive constructs in TRAFFIC, e.g., allowing for type variables

Type-disciplined, Scalable, Practical Composition of Networked Services

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(and maybe some of you ☺)

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