Reasoning about Active Network Protocols

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Active Networking

Active networks provide a *programmable* user-network interface.

Users can:

- transmit packets
- *inject* code describing how [their] packets should be handled.

Benefits:

- Speed deployment of new services and algorithms.
- Improve service by exploiting the *combination* of application- and network-supplied information, e.g.: congestion onset; data dependencies.

Approaches to Programmability

Granularity

- per packet, in-band
- per flow, in-/out-of-band
- per node

What kind of abstract machine interprets the injected code?

- static (e.g. IP, ATM)
- pre-customized = code selects from menu (e.g. library)
- Turing machine

By Whom?

- end users vs. service providers vs. developers

The Problem

Conflicting Objectives:

- State global network properties that hold independent of injected code.
- Allow injected code to specify arbitrary behaviors.

Node behavior $\equiv$ fixed part + variable part

fixed part defines (e2e) behavior:	network properties easier to show
	limited flexibility
variable part defines (e2e) behavior:	full flexibility
	can't prove much *a priori*

CANEs Approach

- Define *generic* packet processing behavior(s) of nodes.
- Define specific points (slots) where behavior can be modified.
- Provide canned behaviors to go in slots, allow *injection* of user-defined slot programs.

Example: Forwarding Behavior

Parse packet, obtain *src, dest, fwding table id, auth token*

$\langle$**Slot 0:[null]**$\rangle$ $\{$marker to src, cache payload, send ack to prev. hop$\}$

i := **Lookup**(*src, dest, fwding table*)

if $i = \perp$ then $\langle$**Slot 1:[null]**$\rangle$ $\{$error message to *src*$\}$

$\langle$**Slot 2:[null]**$\rangle$ $\{$snd i to *src*, authenticate $i\}$

if i is congested then $\langle$**Slot 3:[discard]**$\rangle$ $\{$queue manipulation$\}$

$\langle$**Slot 4:[null]**$\rangle$ $\{$(local) smoothing, scheduling$\}$

enqueue packet for i.

Define services by injecting/selecting code in slots.

Language Independent Active Network Environment

Active node behavior defined by **underlying program**, plus **injected program(s)** bound to **slots**.

- A formal model using UNITY notation and logic
- Underlying programs interact with injected programs via shared variables.
- Slots are *raised* to enable the injected code.
- Each slot has resource bounds, restrictions and obligations of injected code. (Syntactically checkable.)

Why UNITY?

- Single composition operator $\|$ allows a simple model of injection and resource-bounding mechanisms.
- Well-understood logical machinery.

Underlying Program

Program {**Node**} *Program at each active node v*

initially

N0 $v.state, discCnt, errCnt = idle, 0, 0$ { Initialization }

assign

N1 $\langle \langle \, [\!] \, x : v.inC[x] \in v.inC :$
$v.state, v.inC[x], v.Msg, v.LH := newPkt, \mathrm{tail}(v.inC[x]), \mathrm{head}(v.inC[x]), x\rangle$
$\| \ \langle \| \, i :: v.rt.i.usage := 0\rangle$
$\rangle$ if $v.idle \wedge (v.inC[x] \neq \bot)$
{ If channel is non-empty, read message and initialize usage counters }

N2 $[\!]$ $v.state := slot.0.raise$ if $v.newPkt$ { Raise message arrival event }

N3 $[\!]$ $v.state, v.NH := rtFound, v.RtTable(v.Msg.d)$ if $v.slot.0.cmpl$
{ Route message to proper channel }

N4 $[\!]$ $v.state := slot.1.raise$ if $v.rtFound$ { Raise routing done event }

N5 $[\!]$ $\langle v.state, \; v.outC[v.NH] := idle, \; v.outC[v.NH]; v.Msg$
$\| \ \langle \; discCnt := discCnt + 1 \;$ if $\; end(v.outC[v.NH]) = NullProc$
$[\!] \; errCnt := errCnt + 1 \;$ if $\; end(v.outC[v.NH]) = ErrProc\rangle\rangle$
if $v.slot.1.cmpl$ { Send message on proper channel; Update Counters }

end $\{Node\}$

Underlying Program — Default Slot Behavior

Program $\{$**DS**$\}$ *Default Slot*

initially

D0 $\langle [\!] \, i :: v.rt.i.usage, v.rt.i.bnd = 0, \beta_i \rangle$ $\{$ Initialization, $\beta_i \geq 0$ $\}$

always

D1 $\langle [\!] \, i :: v.SlotCnd.i = (v.rt.i.bnd > v.rt.i.usage) \wedge v.slot.i.raise \rangle$

$\{$ Default set of conditions for progress through slot $\}$

D2 $\langle [\!] \, i :: v.Prog.i = Q.i \rangle$

$\{$ "background" predicate Q, set to $\mathtt{true}$ if no programs are bound to slot i $\}$

assign

D3 $\langle [\!] \, i :: v.rt.i.usage := v.rt.i.usage + 1$ if $v.SlotCnd.i \wedge v.Prog.i \rangle$

$\{$ Increase resource usage if no other program active $\}$

D4 $[\!] \, \langle [\!] \, i :: v.state := v.slot.i.cmpl$ if $v.slot.i.raise \wedge v.rt.i.bnd = v.rt.i.usage \rangle$

$\{$ Resource bound exhausted, slot processing complete $\}$

end $\{DS\}$

General Results

Definitions

- Well-formedness (*receptivity*) of underlying program
- Well-formedness (*acceptability*) of injected program
- Injection transformation, combines with default slot program

Metatheorems

- Injection preserves receptivity.
- Injection distributes over $\|$.
- Injection preserves properties of (underlying program $\|$ injected program).
- Injection preserves *pure* properties of injected program, modulo resource bounds.

Properties of Underlying Program

- Messages eventually reach their destinations.

Example: Mobility

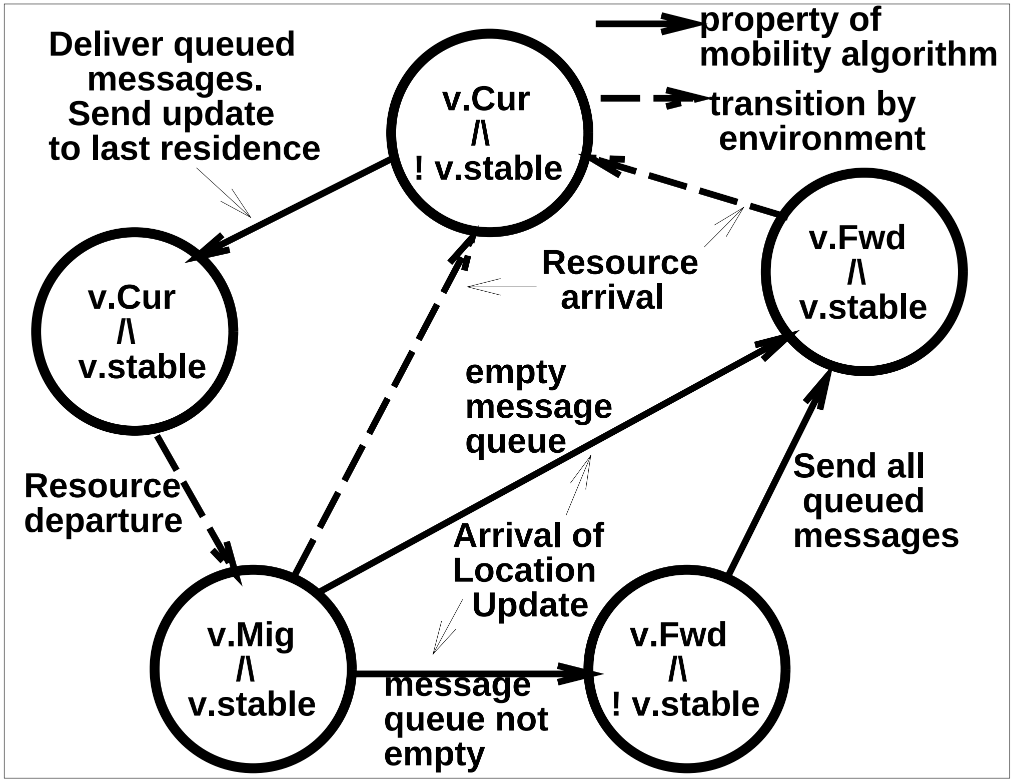
The Problem

- A *resource* migrates spontaneously from node to node.
- Messages are addressed to the “last known address” of the resource.
- Nodes keep pointers to resource location, forward messages toward it.

The Approach

- Bind code for mobility to slot 0.
- Messages for the resource carry last-known location, plus a (logical) timestamp.
- When nodes see messages with newer timestamps, they update their pointers to the resource.
- When resource arrives at a node, it increments timestamp and sends an update to the previous location in the message.

Mobility Example



Properties

- Messages not addressed to the resource reach their destination.
- Messages reach either the resource or a node with newer information.

Mobility Example

Program $\{$**Mobility**$\}$ *Mobility Code for Slot 0*

initially

MA0 $v.rState, v.rLC, v.rLoc, v.rStable, v.rQ = Fwd, 0, r.home, \text{true}, \perp$
$\text{if } v \neq r.home \sim Cur, 0, v, \text{true}, \perp \text{ if } v = r.home$

$\{$ Resource r is initially located at $r.home$; this is known to all other nodes $\}$

assign

MA1 $v.Msg.d, v.Msg.loc, v.Msg.ts := redir(v.rLoc, v.Msg.d), v.rLoc, v.rLC$
$\text{if } v.rLC > v.Msg.ts \wedge v.Msg.type = Access \wedge (v.Fwd \vee v.Cur) \wedge v.stable$

$\{$ Re-direct accesses containing stale information $\}$

MA2 $v.rLoc, v.rLC := v.Msg.loc, v.Msg.ts \text{ if } v.rLC < v.Msg.ts \wedge v.Fwd \wedge v.stable$

$\{$ Update local clock and forwarding information if message contains newer information $\}$

MA3 $\langle fwd\ (Qh.s, redir(v, Qh.d), Qh.r, v, res.ts + 1, Qh.type, Qh.body)$
$\parallel\ v.rQ := \text{tail}(v.rQ)\rangle \text{ if } v.Cur \wedge \neg v.stable \wedge v.rQ \neq \perp$

$\{$ Resource arrives at node v; Deliver all queued messages $\}$

. . . etc.

Finis

Conclusions

- A model of active node programming using UNITY
- The slot model is intended to permit reasoning about global behavior with limited knowledge of the injected program.
- We still need strong/precise constraints on the injected program to guarantee underlying properties (e.g. every message reaches its destination).
- Mobility as an application for active nets

Future Work

- Other applications: reliable multicast. . .
- Reasoning about behavior *during* injection, when some nodes have the injected code and some don't.