Scalaness/nesT: Type Specialized Staged Programming for Sensor Networks

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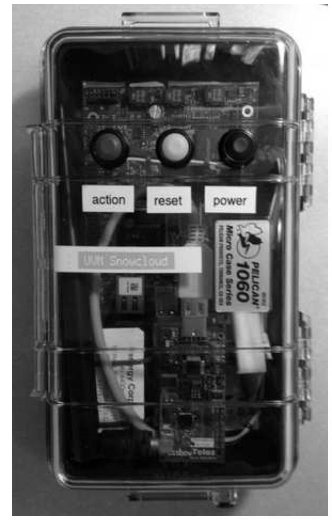
The Problem Setting: Embedded Sensor Networks



- Distributed data-gathering systems for earth and agricultural sciences.
- At UVM, focus on alpine snow hydrology.
  - Deployments in California, New Hampshire, Arctic Norway.

Challenges of Programming Sensor Networks

- Heavily resource constrained—RAM, ROM, clock cycles, power.
- e.g., Crossbow TelosB: 4 MHz, 10 KiB RAM, 48 KiB ROM
- . . . yet complex, distributed algorithms used.

State of the art:

- nesC and TinyOS: Optimized for efficiency, widely used.

nesC Modules

```
#include "Message.h"

module SendC {
  uses error_t radio_x(Msg*);
}
implementation {
  ...
}
```

```
#include "Message.h"

module RadioC {
  provides error_t radio_x(Msg*);
  uses error_t handle_radio_r(Msg*);
 }
 implementation {
   ...
 }
```

- Modules consist of a specification and implementation.
- Specification lists used and provided *commands*.
- Implementation is a C-like translation unit.

nesC Configurations

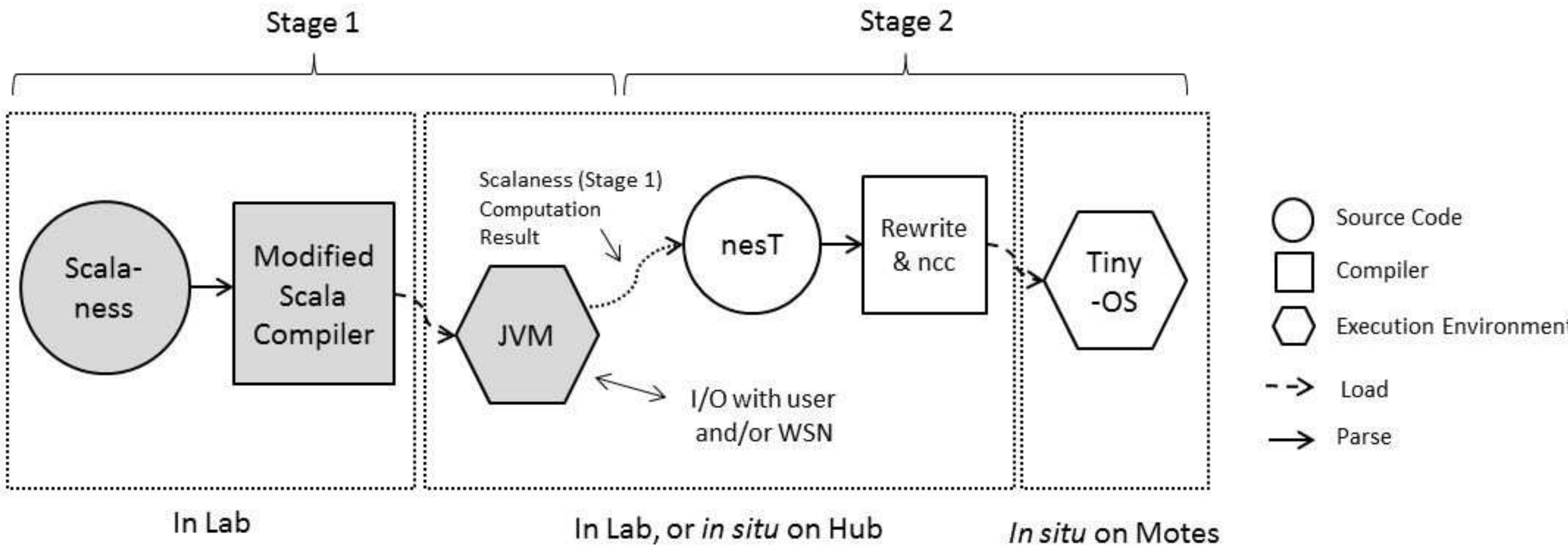
```
configuration AppC { }
implementation {
  components SendC, RadioC;
  SendC.radio_x -> RadioC.radio_x;
}
```

- Application formed by *wiring* components together.
- Component wiring is entirely static.
- Example above incomplete: unresolved import.

Our Approach

- *Staging with two stages*. Scala at metalevel, nesC residuum. Modules are the smallest unit of code manipulation.
- Technical features: *Type specialization* with *dynamic type construction*, *process separation*.
- *Cross-stage type safety*: Type checking at Scala level ensures type safety of nesC residuum.
- *Well-founded language design*.

Workflow



- *In the lab*: First stage program specializes and composes modules of second stage code.
- *In the field*: Generated second stage program accounts for field conditions. Deployed to nodes (over the air).

Example: Introducing Some Type Abbreviations

```
abbrvt mesgT(t) =
  { src : t; dest : t; data : uint8[] };

abbrvt radioT =
  < at ≼ uint32 >
  { export error_t radio_x(mesgT(at)*);
    import error_t handle_radio_r(mesgT(at)*); };
```

- A record type parameterized by a type `t`.
- nesT modules parameterized by types and values.

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Example: nesT Modules

```
val authSend =
  < at ≼ uint32; sendk : uint8[] >
  { import error_t radio_x(mesgT(at)*);
    export error_t send(m : mesgT(at)*)
          { radio_x(AES_sign(m, sendk)); }
  };
```

- First stage manipulates entire nesT modules.

Example: Scalaness Method

```
def authSpecialize
 (nmax   : Int,
  radioM : radioT,
  keys   : Array[Array[uint8]]) : commT {

    typedef adt ≼ uint32 =
      if (nmax <= 256) uint8 else uint16;

    val sendM = authSend⟨adt;keys(0)⟩;
    val recvM = authRecv⟨adt;keys(1)⟩;
    sendM ⋉ radioM⟨adt⟩ ⋉ recvM;
}
```

- Types constructed during first stage execution.
- Values lifted from one stage to the next only at module instantiation.
- Wiring operator composes fully instantiated modules.

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Example: Generating Residual Program

```
image(appM ⋉
        authSpecialize(nmax, radioM, keys) ⋉
          appMR);
```

- Type system ensures imaged module is “runnable.”
- `image` writes nesC residuum at run time.
- Values serialized across process spaces at first stage run time.
- Arbitrary nesC wrapped in special *external modules*.

Implementation

Scalaness/nesT has been implemented.

- nesT defined as restricted subset of nesC, compiled as nesC with some rewriting (e.g. array bounds checks).
- Scalaness defined by extension to the Scala compiler.
- Type checking extends Scala type checker with module types, module operation typings, nesT type checking.

Web site with samples: `http://tinyurl.com/a85z8cu`

Application: WSN Session Key Negotiation

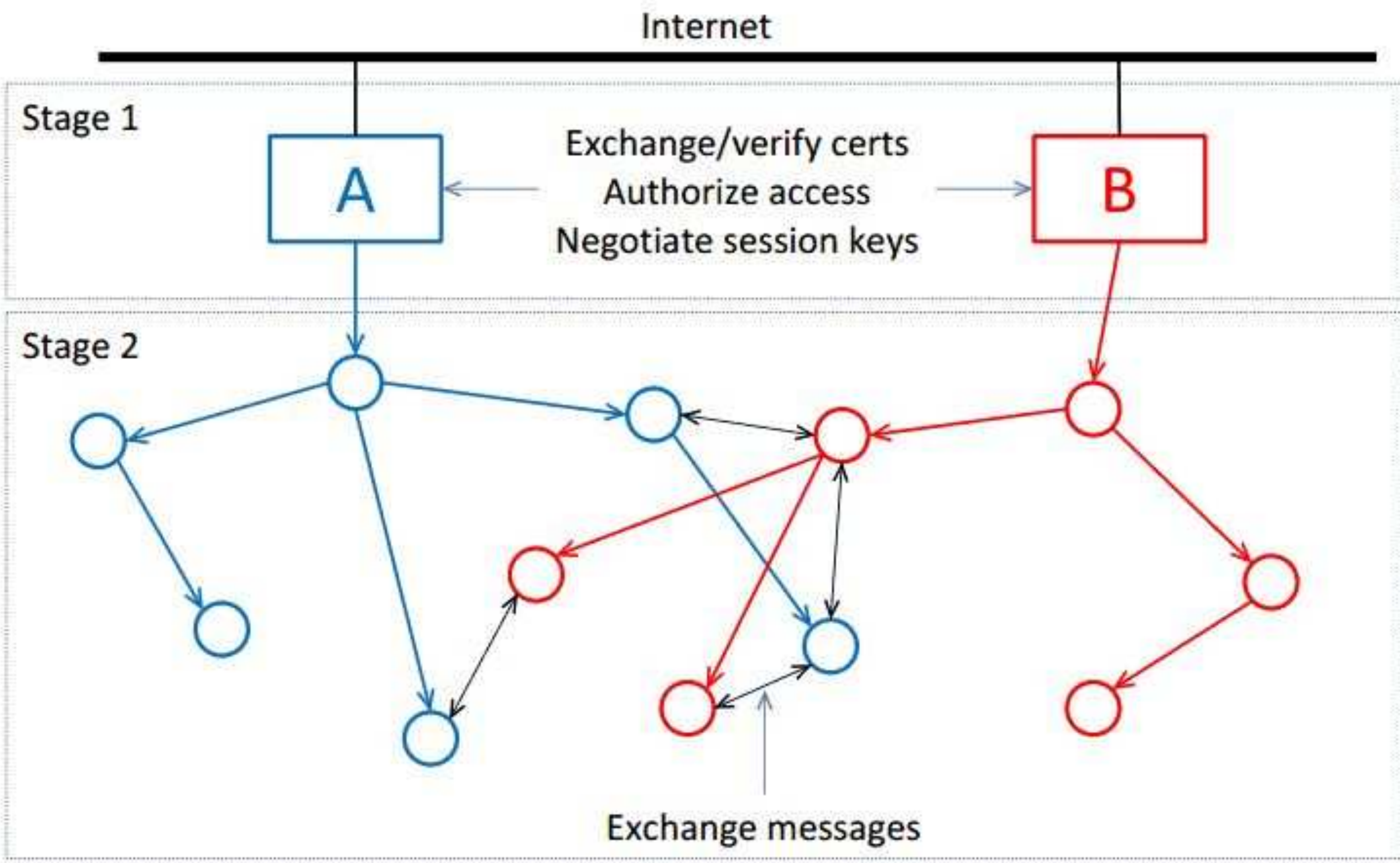
Currently studying authorization schemes for WSNs.

- WSN may comprise interacting security domains wishing to (partially) share resources.
- Symmetric keys provide efficient foundation for securing access.
- Public keys allow symmetric key negotiation in an “open world” model.

Public key signature verification expensive in WSNs; around 90 seconds on Crossbow TelosB.

Refactor authorization decision and session key negotiation into different stages.

Application: WSN Session Key Negotiation



Decreases WSN computational overhead, RAM and ROM consumption.

Results

	Unsecured	Unstaged*	Staged	Savings
Sensor ROM	36254	48616	36596	25%
Sensor RAM	2868	5417	3038	44%
Harvester ROM	24316	35834	24436	32%
Harvester RAM	2274	4771	2402	50%

- Security model: Two different Harvester “nodes”

  1. Data download only.
  2. Data download and control.

* Chapin, Skalka; *SpartanRPC*; Technical Report; `http://www.cs.uvm.edu/~skalka/skalka-pubs/chapin-skalka-spartanrpctr.pdf`

Future Work

- Clarifying “middle ground” between language borders.
- Syntactic transformations: Allowing more natural syntax in Scalaness programs.
- Incorporating network communication.
- Other applications: Backcasting and evolving control.

Questions?

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http://tinyurl.com/a85z8cu

$\langle$ML$\rangle$ Foundations

The $\langle$ML$\rangle$ language* was developed to study these elements at a foundational level.

- MetaML-like syntax and semantics, but novel features to moderate interactions between separate process spaces.
- Comprises $F_{\leq}$.
- Resricted form of type construction (not full λ_{ω}).
- Formal metatheory includes cross-stage type safety—residue of partial evaluation of well-typed code is guaranteed to be well-typed.

Yu David Liu, Christian Skalka, and Scott Smith. Type-Specialized Staged Programming with Process Separation. Journal of Higher Order and Symbolic Computation, 24(4):341-385, 2012.

Sample Scalaness Typing

$$\Delta_1 \circ <\Delta_2, \Gamma>\{\iota; \varepsilon\}$$

Module type form, where:

- Δ_2, Γ type parameter bounds and term parameter types.
- ι, ε import and export type signatures.
- Δ_1 bounds of types constructed externally to the module.
  - Early substitution of these types unsound due to possible contravariant use in $\iota; \varepsilon$.

MODINSTT

$$\frac{\begin{array}{c}\Gamma \vdash \mathtt{e} : \varnothing \circ <\bar{t} \preccurlyeq \bar{\tau}_1; \bar{x} : \bar{\tau}_2>\{\iota; \varepsilon\} \\ \Gamma \vdash \bar{\mathtt{s}} : \mathtt{MetaType}\langle \bar{\mathtt{T}}_1 \rangle \qquad \Gamma \vdash \bar{\mathtt{e}}_2 : \bar{\mathtt{T}}_2 \qquad \vdash [\![\bar{\mathtt{T}}_1]\!] \preccurlyeq \bar{\tau}_1 \qquad \vdash [\![\bar{\mathtt{T}}_2]\!] \preccurlyeq \bar{\tau}_2\end{array}}{\Gamma \vdash \mathtt{e}\langle \bar{\mathtt{s}}; \bar{\mathtt{e}}_2 \rangle : \bar{\mathtt{s}} \preccurlyeq [\![\bar{\mathtt{T}}_1]\!] \circ <>\{\iota[\bar{\mathtt{s}}/\bar{t}]; \varepsilon[\bar{\mathtt{s}}/\bar{t}]\}}$$