Automatisierte Logik und Programmierung

Einheit 16

Anwendungsbeispiele

1. Mathematik:
   Automatisierung von Kategorientheorie
2. Programmierung:
   Analyse und Optimierung verteilter Systeme
3. Aktuelle Fragestellungen:
   Language-based Security

Automating Proofs in Category Theory

- **Category Theory analyzes structure**

  What properties of mathematical domains depend only on structure?

  · Focus on mathematical objects and morphisms on these objects

  · Develop a generic framework for expressing abstract properties

  – Results have a wide impact on mathematics and computer science

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  – Key insights are often considered “the only obvious choice”
  - · It should be possible to write tactics that construct proofs

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- **Formulate as first-order reasoning system**
  - Rules about products, functors, natural transformations, ...
  - Analysis and synthesis of structures
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  - Equational reasoning is essential in most proofs
- **Example: Analysis rules for functors**
  - Rules essentially explain what functors are and how to use them

$$\frac{\Gamma \vdash F : \mathsf{Fun}[\mathsf{C},\mathsf{D}], \quad \Gamma \vdash \mathsf{A} : \mathsf{C}}{\Gamma \vdash F^1 A : \mathsf{D}}$$

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Non-conservative extension with CTT support

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  - Display forms intruduce MacLane’s textbook notation

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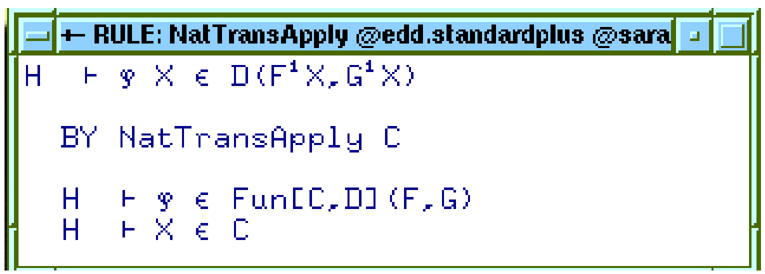
  - Introduce (top-down) rule objects for each inference rule



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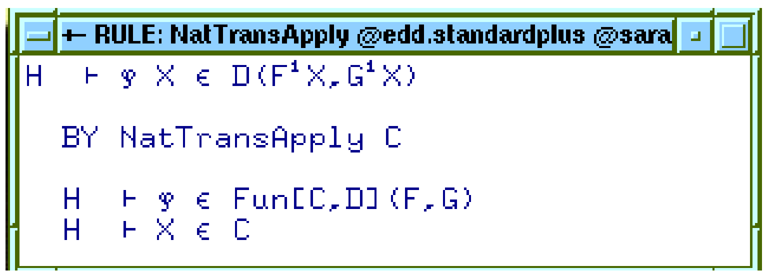

  - Justify inference rules by proving them correct in CTT
  - Convert primitive inferences into simple tactics

PROOF AUTOMATION

- **Most steps are straightforward decompositions**
  - Apply analysis and synthesis rules where possible
  - Block application of analysis rules that create subgoals previously decomposed by a synthesis rule
  - Assert goals that will re-occur several times in subproofs

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- **Guess witnesses for existential quantifiers**
  - Introduce meta-variables for existentially quantified variables
  - Decompose as long as possible and focus of typing subgoals
  - Introduce the simplest term that satisfies the typing requirements

An example proof

*- PRF : Currying Tactic Test @edd.standardplus @sarah

```
* top
∀C,D,E:Categories.  Fun[C×D,E] ≙ Fun[C,Fun[D,E]]

BY Unfold `CatIso` 0 THEN prover·

* 1

1. C : Categories
2. D : Categories
3. E : Categories
⊢ ∃ϑ:Fun[Fun[C×D,E],Fun[C,Fun[D,E]]].
  ∃η:Fun[Fun[C,Fun[D,E]],Fun[C×D,E]]. ϑ and η are inverse

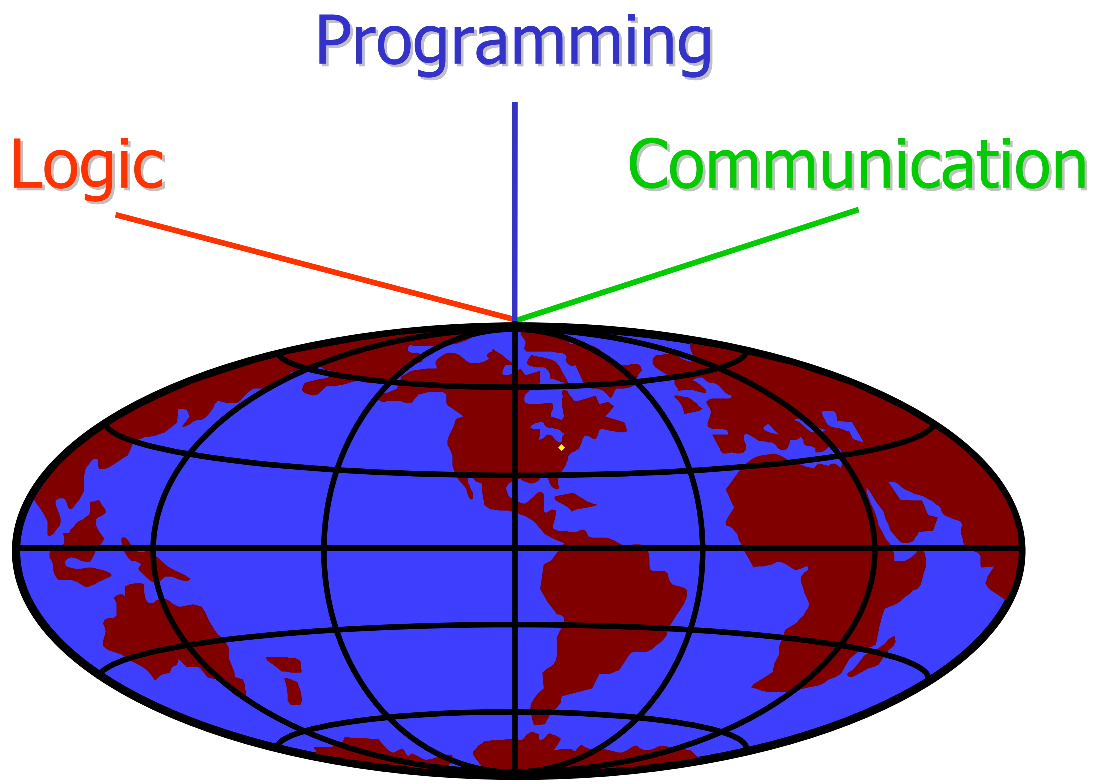
BY GUESS ⌜ϑ⌝ THEN GUESS ⌜η⌝·

* 1 1

4. theta : Top
5. ∀phi,k,X1,X,f,G:Top.
      (ϑ^1 G^2 f X ≡ G^2 <f, 1X>
      ∧ ϑ^1 G^1 X^1 X1 ≡ G^1 <X, X1>
      ∧ ϑ^1 G^1 X^2 k ≡ G^2 <1X, k>
      ∧ ϑ^2 φ X X1 ≡ φ <X, X1>)
6. eta : Top
7. ∀X1,phi,g,f,X,A,G:Top.
      (η^1 G^1 <A, X> ≡ G^1 A^1 X
      ∧ η^1 G^2 <f, g> ≡ ((G^2 f cod(g))∘G^1 dom(f)^2 g)
      ∧ η^2 φ <A, X1> ≡ φ A X1)
⊢ ϑ and η are inverse

BY Unfold `FunInverse` 0 THEN AutoCAT2
```

Towards Reliable, High-Performance Networks



Secure software infrastructure

Apply Formal Reasoning to a real-world system

The Ensemble Group Communication Toolkit

Modular group communication system

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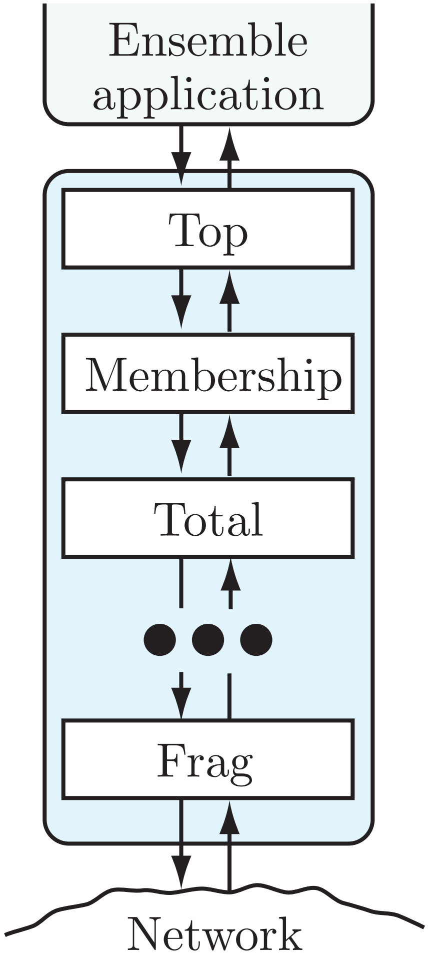

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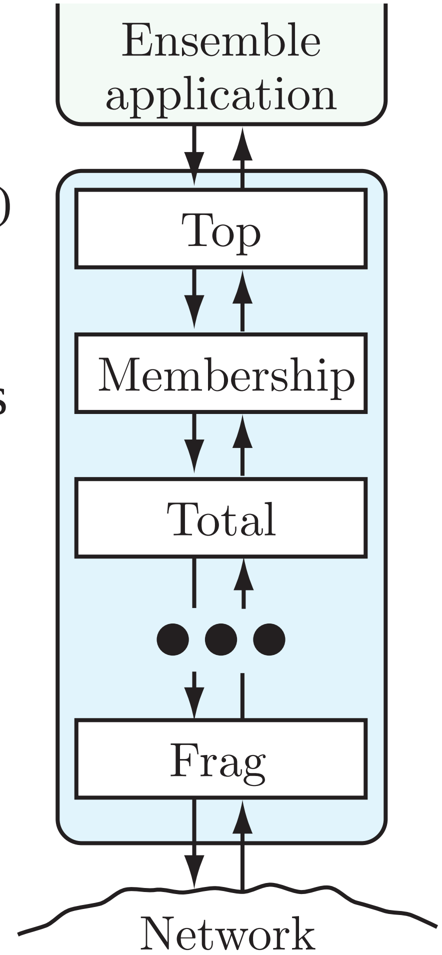

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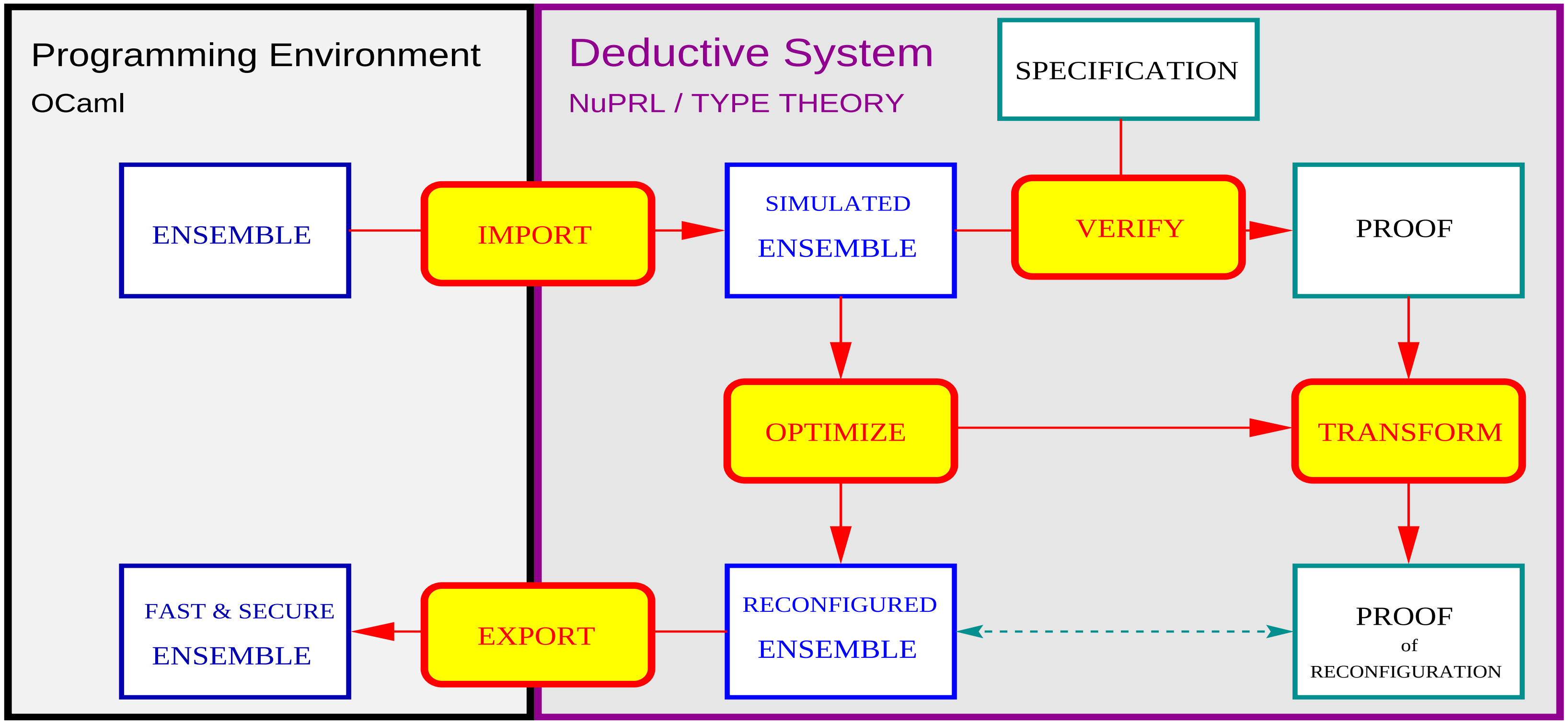
Implementation in Objective Caml (INRIA)

– Easy maintenance (small code, good data structures)

– Mathematical semantics, strict data type concepts

– Efficient compilers and type checkers

Formal reasoning about a real-world system



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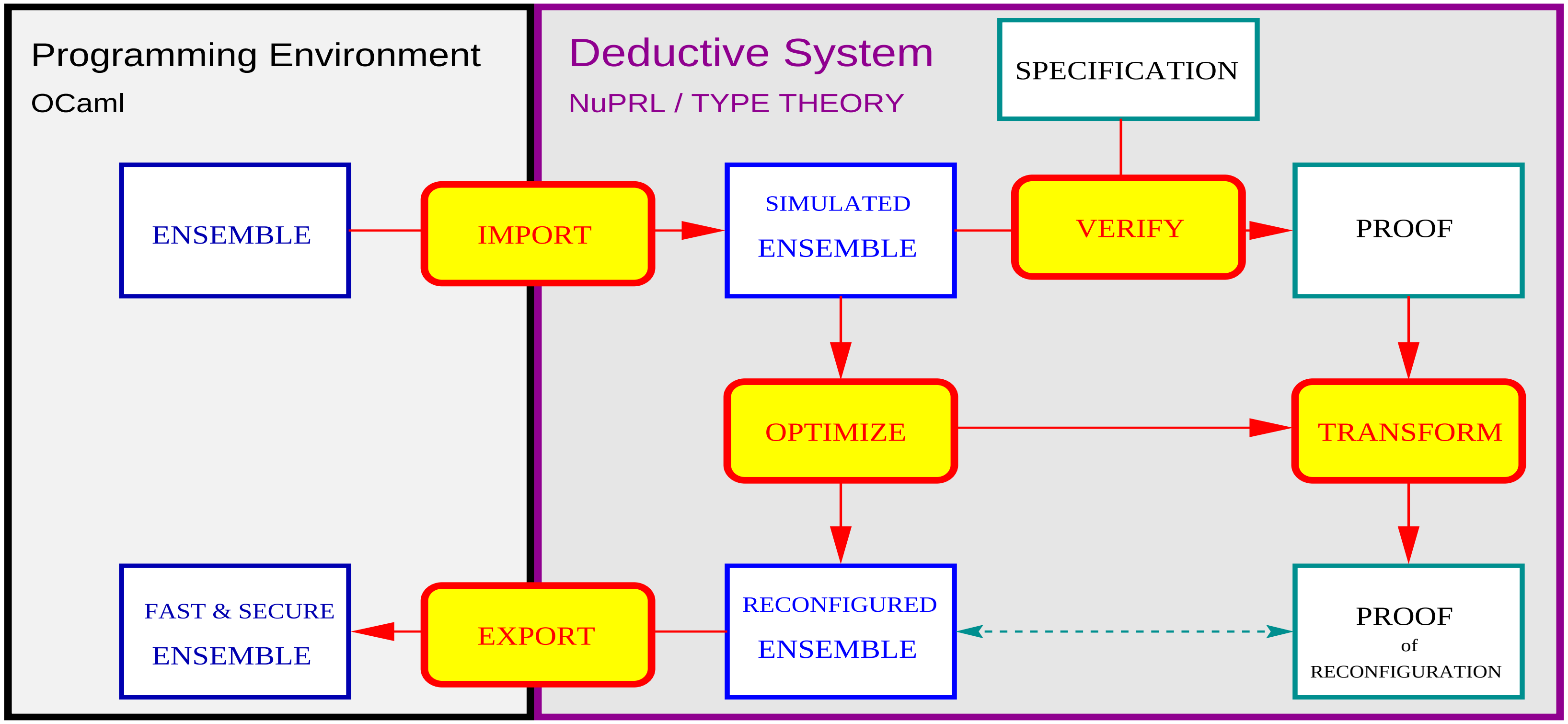
FORMAL REASONING ABOUT A REAL-WORLD SYSTEM



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– Embed ENSEMBLE's code into Nuprl's language

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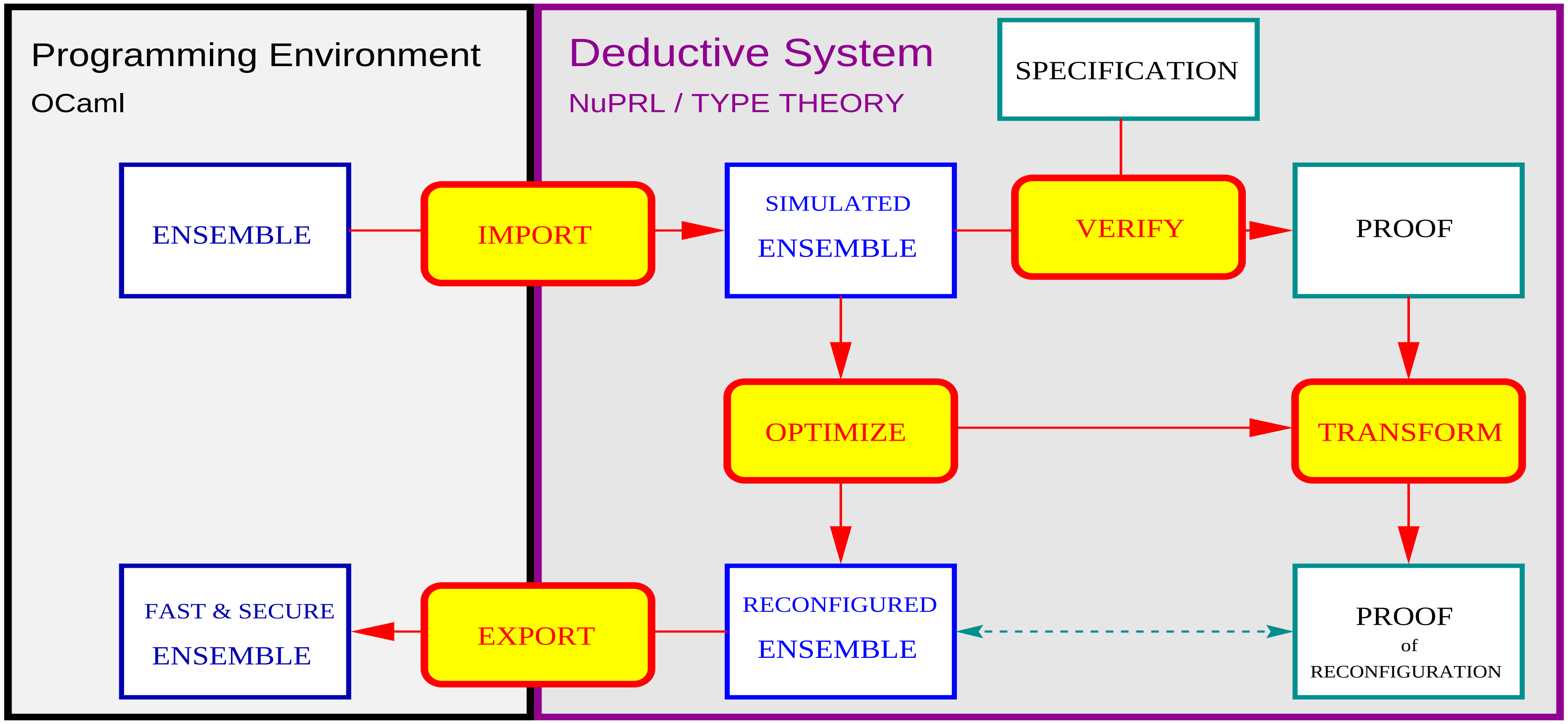

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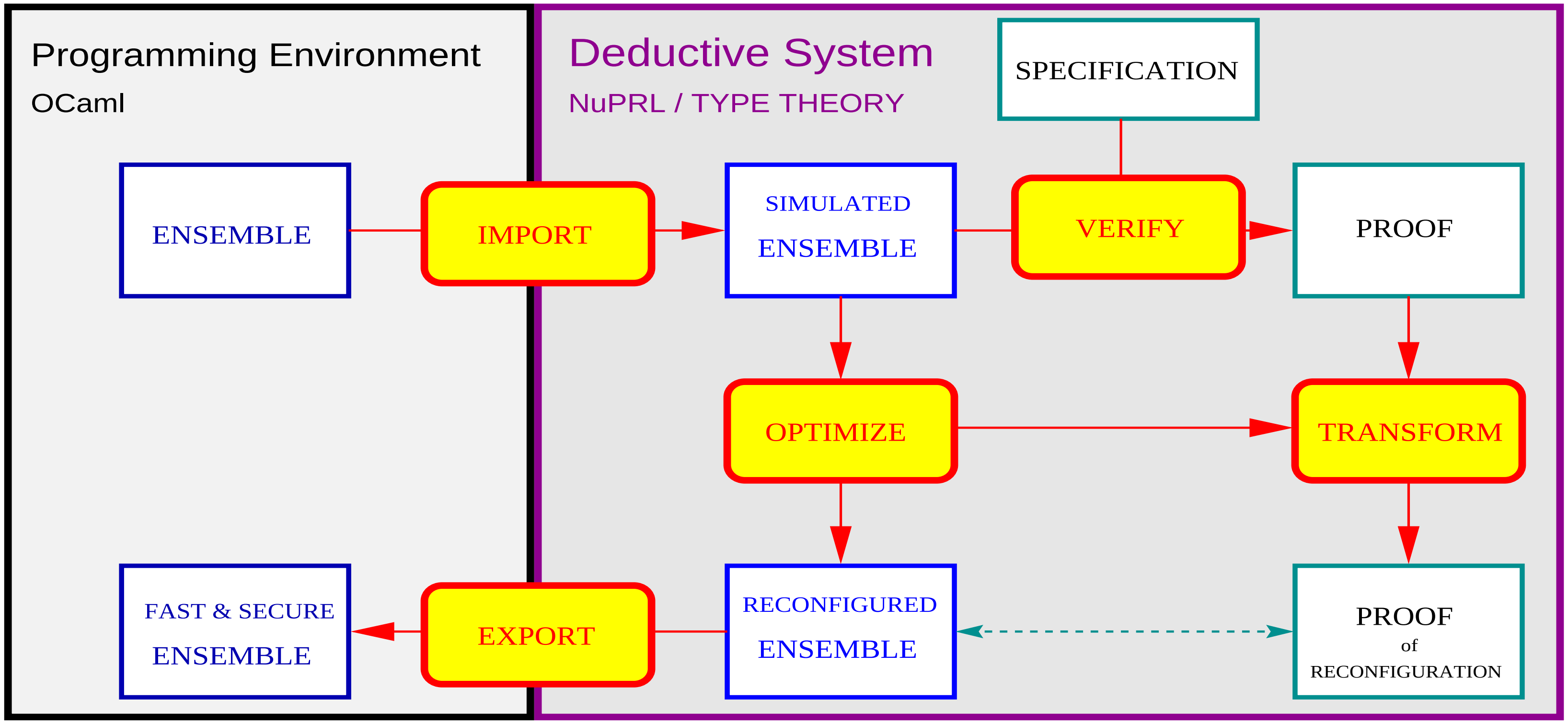

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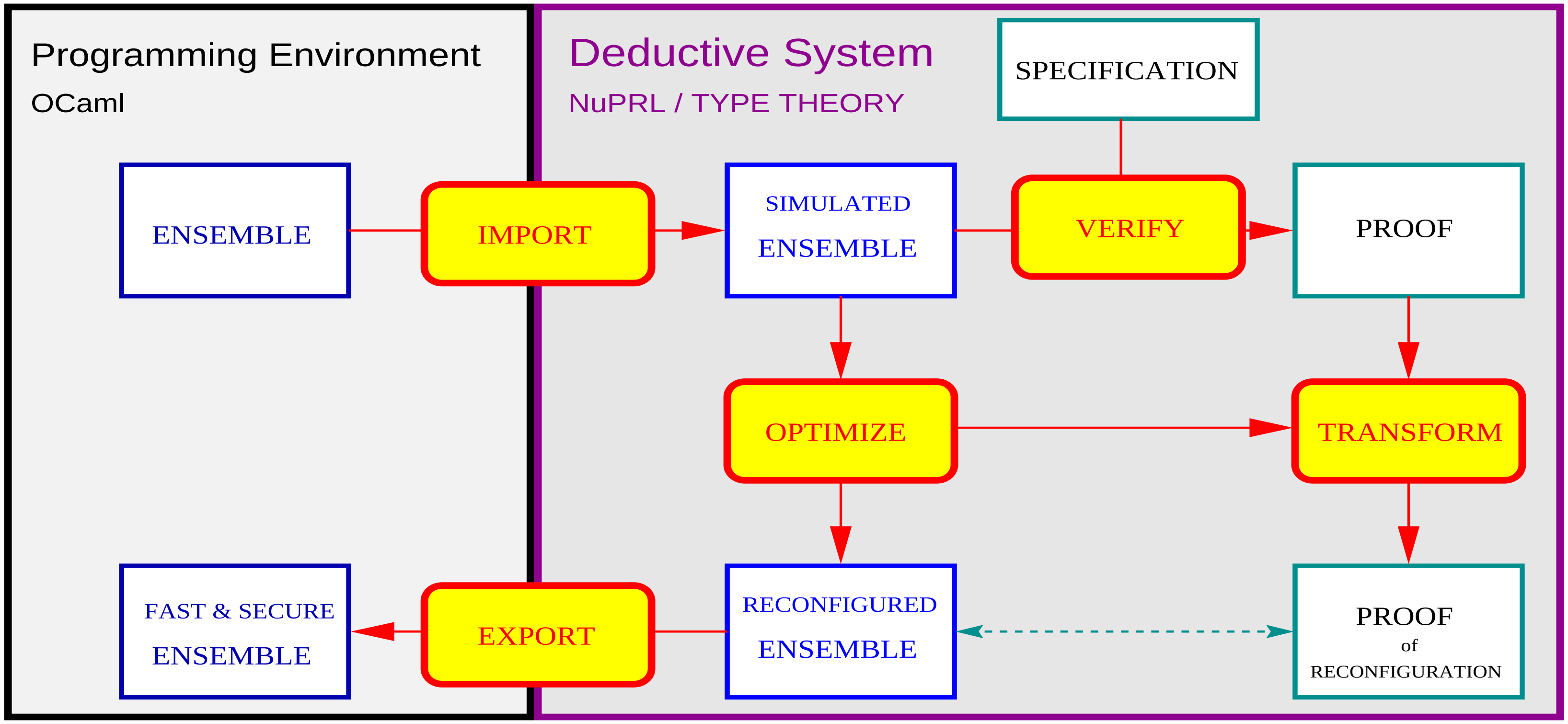

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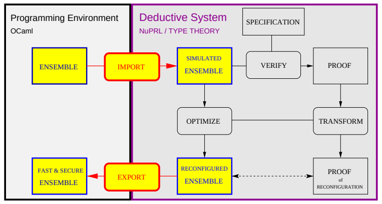
– Formally design and verify new protocols



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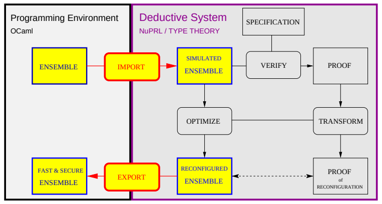

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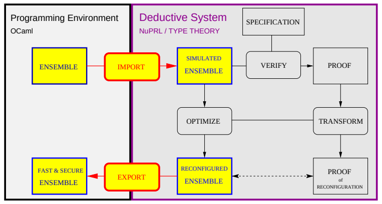

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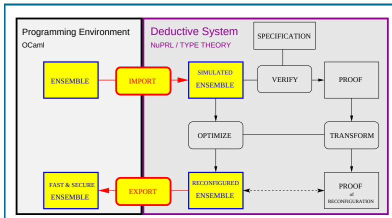

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- **Develop tools for importing and exporting code**
  - Translators between OCaml program text and Nuprl terms

OCaml Semantics: The functional core

- **Basic OCaml expressions similar to CTT terms**
  – Numbers, tuples, lists etc. can be mapped directly onto CTT terms

OCaml SEMANTICS: THE FUNCTIONAL CORE

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- **Complex data structures have to be simulated**

  Records $\{f_1\texttt{=}e_1; \ldots; f_n\texttt{=}e_n\}$ are functions in `f:FIELDS`$\rightarrow T$`[f]`

  - Abstraction for representing the semantics of record expressions

    `RecordExpr(`***field***`;`***e***`;`***next***`)` $\equiv$ λ`f. if f=`***field*** `then` ***e*** `else` ***next*** `(f)`

  - Display form for representing the flexible syntax of record expressions

	{***field***=***e***; ***next***}	$\equiv$	`RecordExpr(`***field***`;`***e***`;`***next***`)`
	{***field***=***e***}	$\equiv$	`RecordExpr(`***field***`;`***e***`;`λ`f.())`
`HD::`	{***field***=***e***; `#`	$\equiv$	`RecordExpr(`***field***`;`***e***`;#)`
`TL::`	***field***=***e***; `#`	$\equiv$	`RecordExpr(`***field***`;`***e***`;#)`
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	{*field*=*e*; *next*}	≡	`RecordExpr(`*field*`;`*e*`;`*next*`)`
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- **Sufficient for representing micro protocols**
  – Simple state-event machines, encoded via updates to certain records
  – Transport module and protocol composition require imperative model

Extensions of the semantical model (1)

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  - OCaml has pattern matching, reference cells, exceptions, modules, …
- **Modelling Pattern Matching:** `let` pat`=`e `in` t

  "Variables of pat in t are bound to corresponding values of e"
  - Evaluation of OCaml-expressions uses an environment of bindings
  - Patterns are functions that modify the environment of expressions

    $x \equiv \lambda\texttt{val},\texttt{t}.\lambda\texttt{env}.\ \texttt{t}\ (\texttt{env@}\{x \mapsto \texttt{val}\})$

    $p_1,p_2 \equiv \lambda\texttt{val},\texttt{t}.\lambda\texttt{env}.\ \texttt{let}\ \texttt{<}\texttt{v}_1,\texttt{v}_2\texttt{>} = \texttt{val}\ \texttt{in}\ (p_1\ \texttt{v}_1\ (p_2\ \texttt{v}_2\ \texttt{t}))\ \texttt{env}$

    $\{f_1{=}p_1;\ ..\ ;\ f_n{=}p_n\} \equiv \lambda\texttt{val},\texttt{t}.\lambda\texttt{env}.\ p_1\ (\texttt{val}\ f_1)\ (..(p_n\ (\texttt{val}\ f_n)\ \texttt{t})..)\ \texttt{env}$

    $\vdots \qquad\qquad \vdots$
  - Local bindings are represented as applications of these functions

    $\texttt{let}\ p{=}e\ \texttt{in}\ t \equiv \lambda\texttt{env}.\ (p\ (e\ \texttt{env})\ t)\ \texttt{env}$

Extensions of the semantical model (2)

- **Modelling Reference cells**
  - Evaluation of OCaml-expressions may lookup/modify a global store
  - The global store is represented as table with addresses and values

$\texttt{ref}(e) \equiv \lambda\texttt{s,env. let <v,}\texttt{s}_1\texttt{>=}e\texttt{ s env in}$
$\qquad\texttt{let addr=NEW(}\texttt{s}_1\texttt{) in <addr, }\texttt{s}_1\texttt{[addr}\leftarrow\texttt{v]>}$

$!e \equiv \lambda\texttt{s,env. let <addr,}\texttt{s}_1\texttt{>=}e\texttt{ s env in <}\texttt{s}_1\texttt{[addr], }\texttt{s}_1\texttt{>}$

$e_1\texttt{:=}e_2 \equiv \lambda\texttt{s,env. let <v,}\texttt{s}_1\texttt{>=}e_2\texttt{ s env in}$
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- **Modelling Exceptions**
  - Expressions like `x/y` may raise exceptions, which can be caught
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- **Modules**
  - Modules are second class objects that structure the name space
  - Modules are represented by operations on a global environment

Summary of the formal model

- OCaml **expressions are represented as functions**
  - Evaluation depends on environment and store
  - Evaluation results in value or exception and an updated store
  - Nuprl type is $\texttt{STORE} \longrightarrow \texttt{ENV} \longrightarrow (\texttt{EXCEPTION} + T) \times \texttt{STORE}$

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  - The standard model for building ML compilers
  - Model combines several mechanisms for evaluating ML programs
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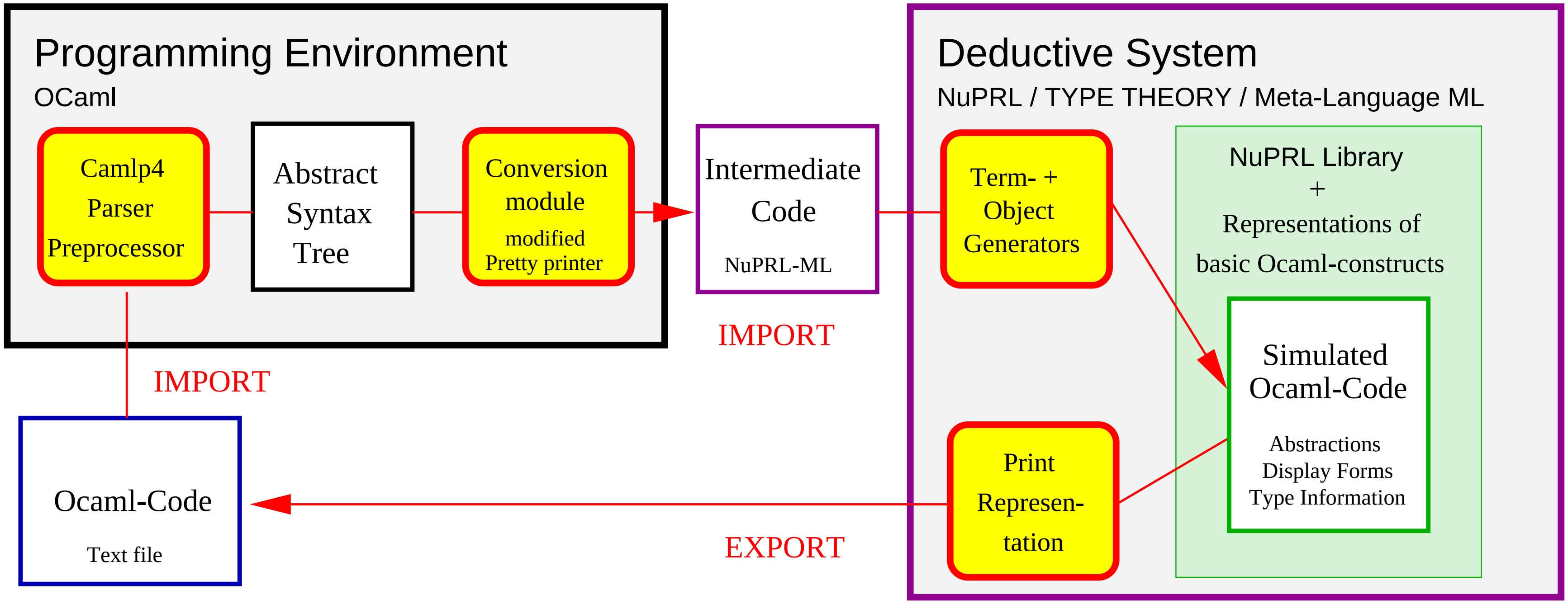
$\Downarrow$

Genuine OCaml code may occur in formal theorems

Importing and Exporting System Code



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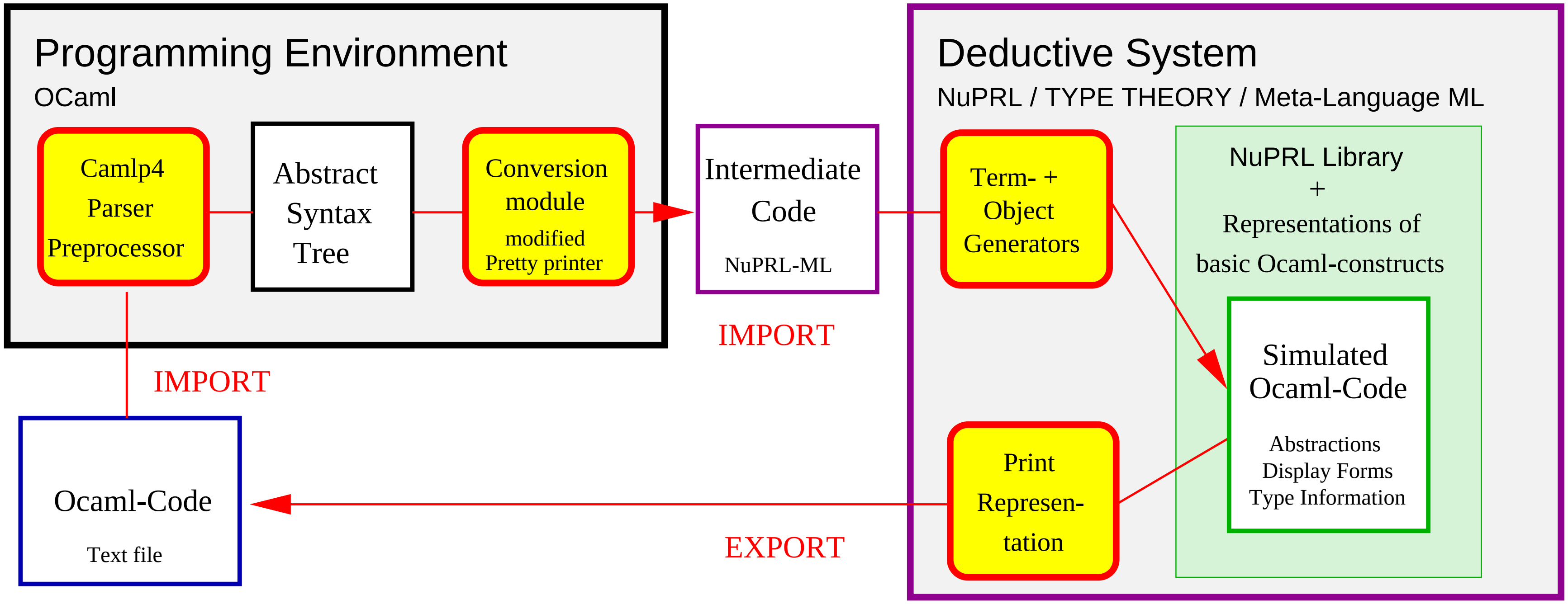

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– Generators perform second pass and create Nuprl library objects

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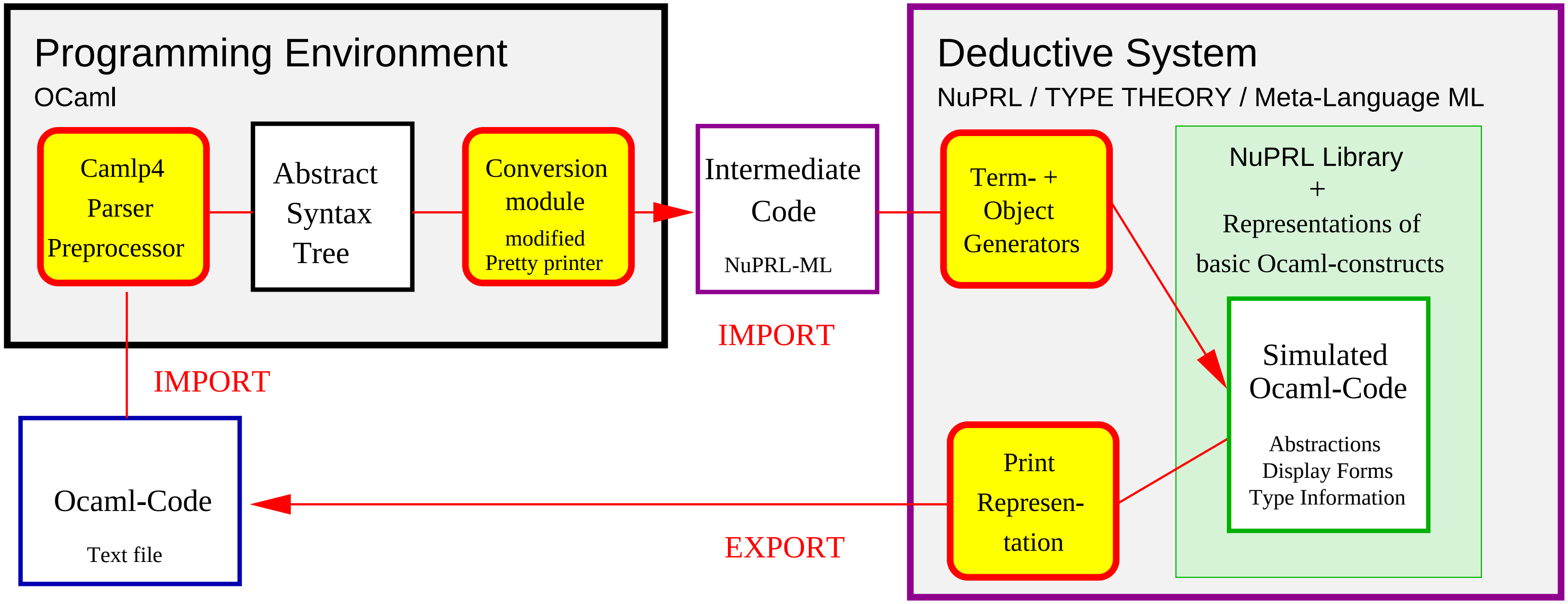

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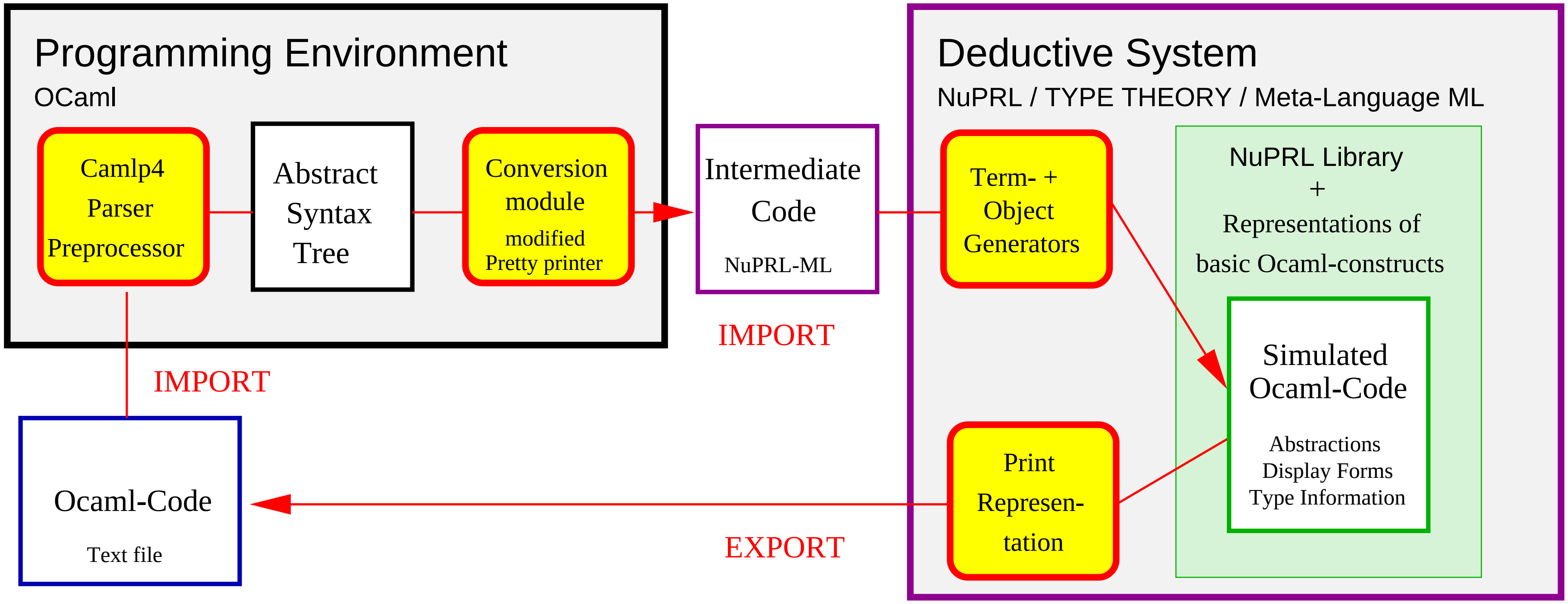
Export: – Print-representation is genuine OCaml-code

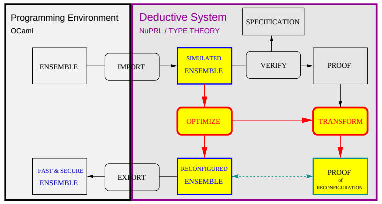
Importing and Exporting System Code



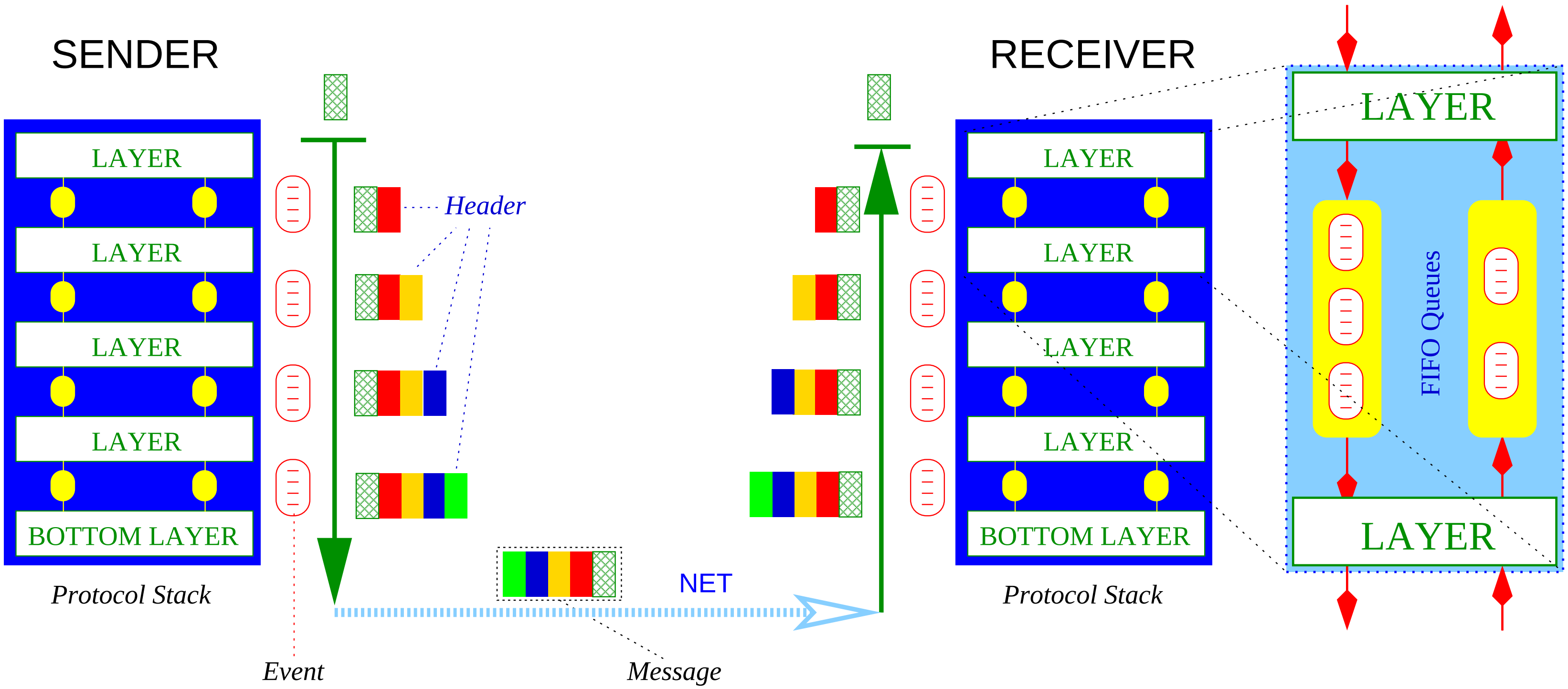
Import: – Parse with Camlp4 parser-preprocessor
– Convert abstract syntax tree into term- & object generators
– Generators perform second pass and create Nuprl library objects

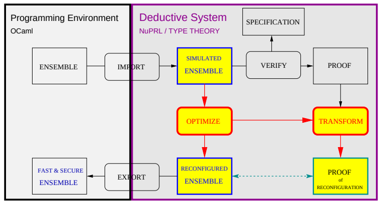
Export: – Print-representation is genuine OCaml-code

Actual ENSEMBLE code available for formal reasoning



Optimization of Protocol Stacks





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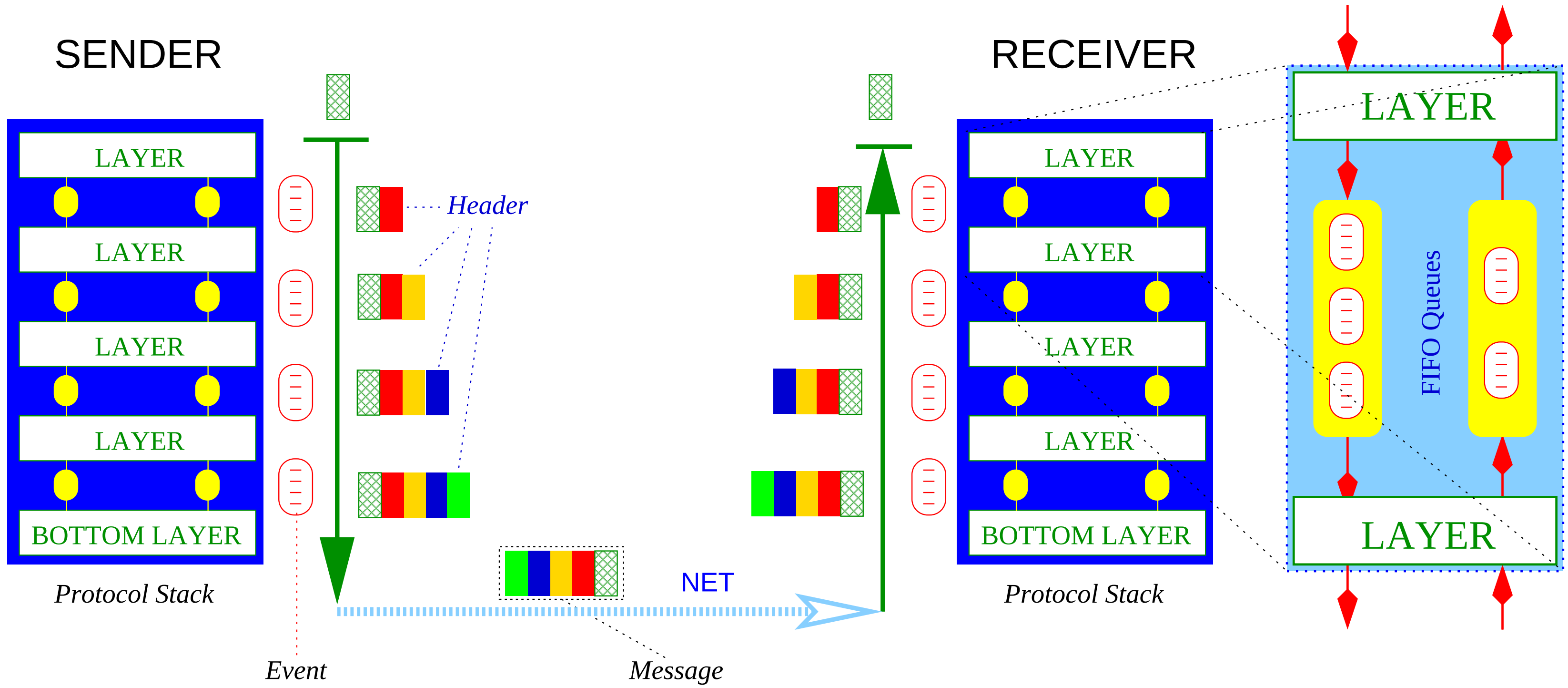
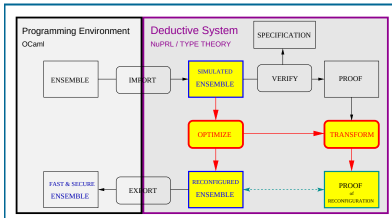


Performance loss: redundancies, internal communication, large message headers



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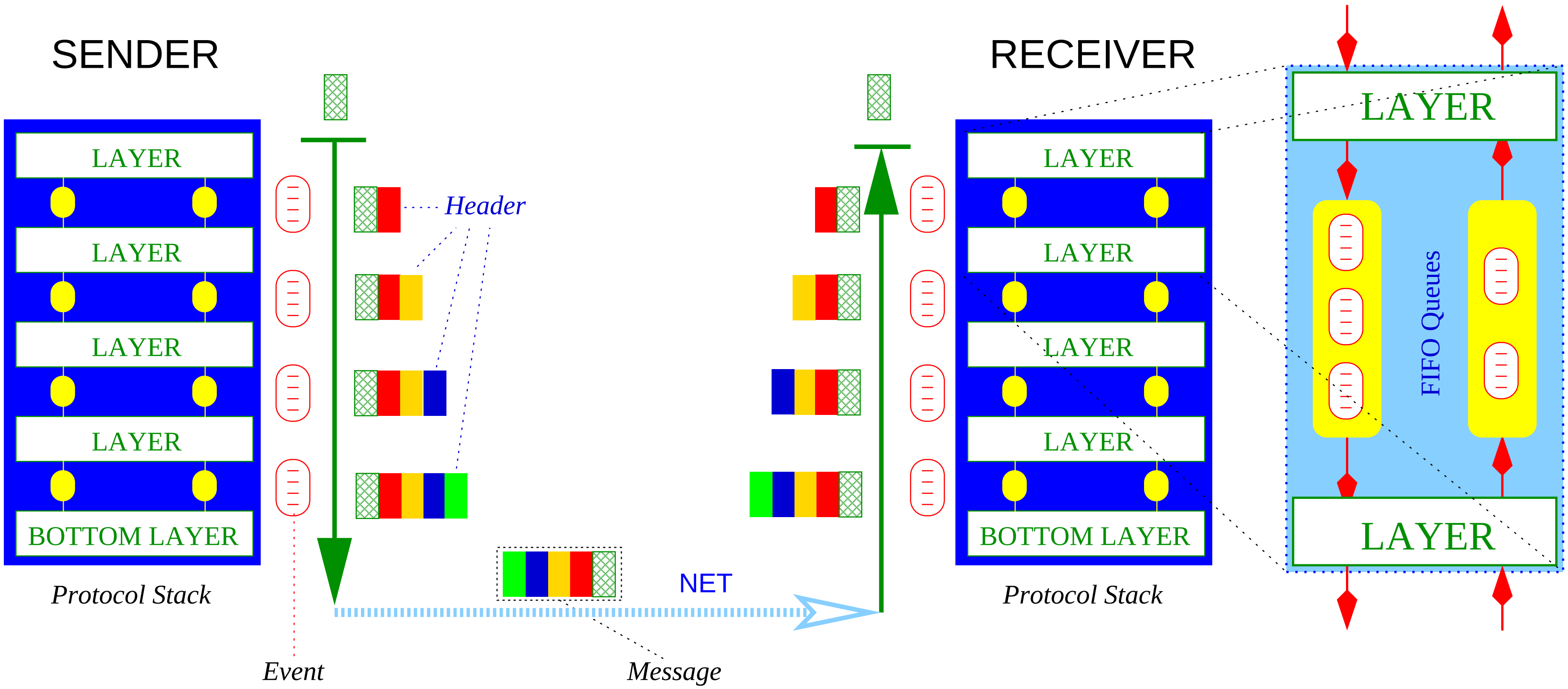

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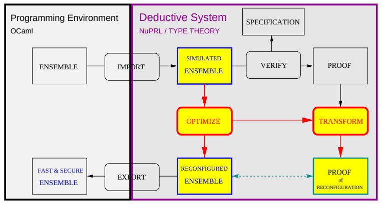

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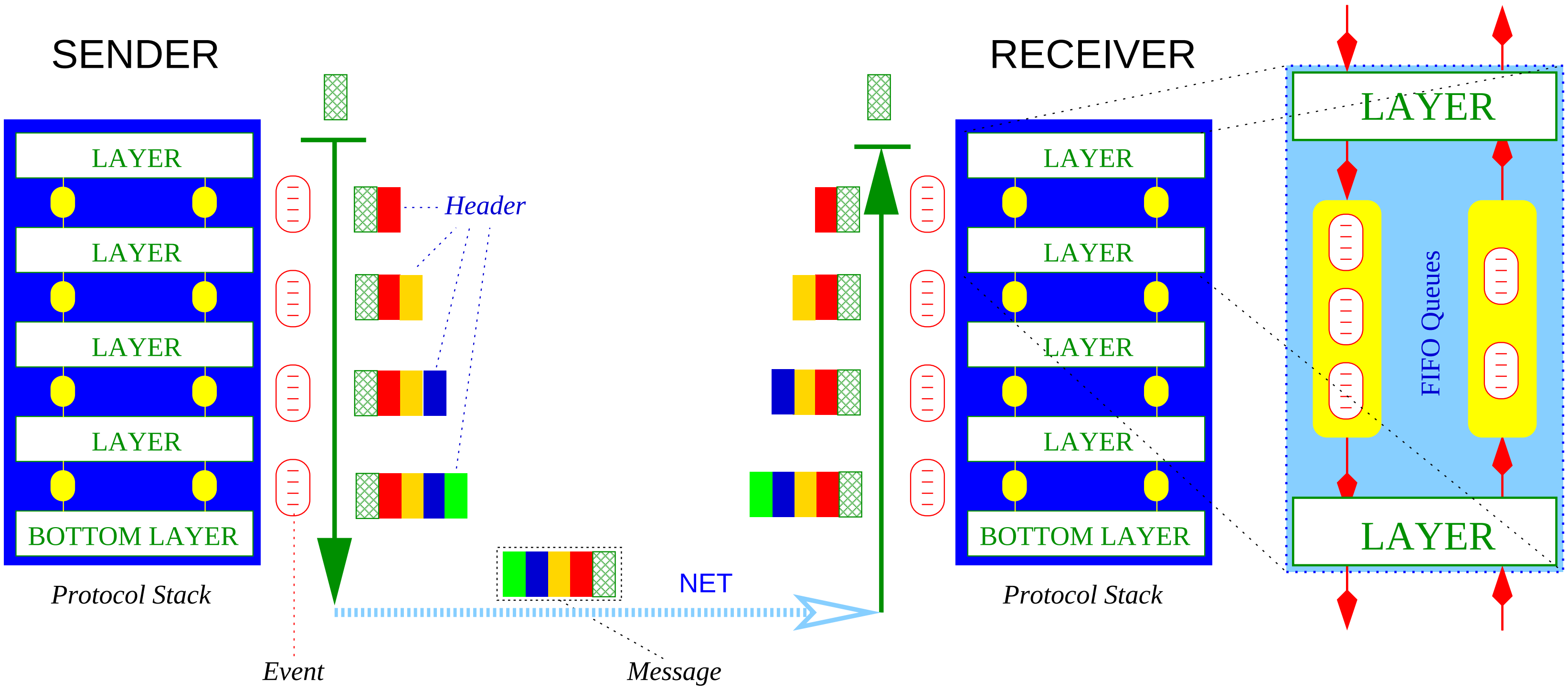

Performance loss: redundancies, internal communication, large message headers

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Need formal methods to do this correctly

Example Protocol Stack Bottom::Mnak::Pt2pt

Trace downgoing Send events and upgoing Cast events

Bottom (200 lines)

```
let name = Trace.source_file "BOTTOM"

type header = NoHdr | ... | ...

type state = {mutable all_alive : bool ; ... }

let  init _ (ls,vs) = {........}

let  hdlrs s (ls,vs)
     {up_out=up;upnm_out=upnm;
      dn_out=dn;dnlm_out=dnlm;dnnm_out=dnnm}
 = ...
 let up_hdlr ev abv hdr =
  match getType ev, hdr with
  | (ECast|ESend), NoHdr ->
    if s.all_alive  or not (s_bottom.failed.(getPeer ev))
       then up ev abv
       else free name ev
  | :
 and uplm_hdlr ev hdr   = ...
 and upnm_hdlr ev       = ...
 and dn_hdlr ev abv     =
  if s.enabled then
    match getType ev with
    | ECast         -> dn ev abv NoHdr
    | ESend         -> dn ev abv NoHdr
    | ECastUnrel    -> dn (set name ev[Type ECast]) abv Unrel
    | ESendUnrel    -> dn (set name ev[Type ESend]) abv Unrel
    | EMergeRequest -> dn ev abv MergeRequest
    | EMergeGranted -> dn ev abv MergeGranted
    | EMergeDenied  -> dn ev abv MergeDenied
    | _ -> failwith "bad down event[1]"
   else (free name ev)
 and dnnm_hdlr ev       = ...
 in {up_in=up_hdlr;uplm_in=uplm_hdlr;upnm_in=upnm_hdlr;
     dn_in=dn_hdlr;dnnm_in=dnnm_hdlr}

let l args vs = Layer.hdr init hdlrs args vs

Layer.install name (Layer.init l)
```

Mnak (350 lines)

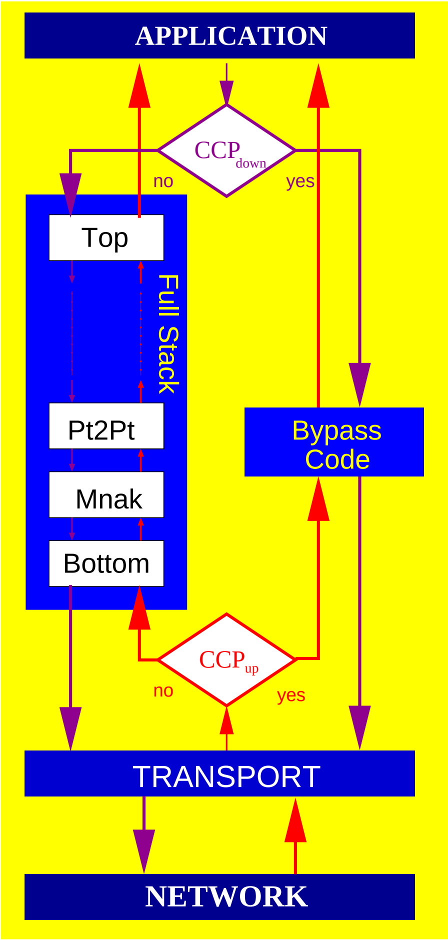
```
let init ack_rate (ls,vs) = {........}
let hdlrs s (ls,vs) { ........ }
 = ...
 let ...
 and dn_hdlr ev abv     =
   match getType ev with
   | ECast ->
       let iov = getIov ev in
       let buf = Arraye.get s.buf ls.rank in
       let seqno = Iq.hi buf in
       assert (Iq.opt_insert_check buf seqno) ;
       Arraye.set s.buf ls.rank
             (Iq.opt_insert_doread buf seqno iov abv) ;
       s.acct_size <- s.acct_size + getIovLen ev ;
       dn ev abv (Data seqno)
   | _ -> dn ev abv NoHdr
   :
```

Pt2pt (250 lines)

```
let init _ (ls,vs) = {........}
let hdlrs s (ls,vs) { ........ }
 = ...
 let ...
 and dn_hdlr ev abv     =
  match getType ev with
  | ESend ->
     let dest = getPeer ev in
     if dest = ls.rank then (
       eprintf "PT2PT:%s\nPT2PT:%s\n"
        (Event.to_string ev) (View.string_of_full (ls,vs));
       failwith "send to myself" ;
     ) ;
     let sends = Arraye.get s.sends dest in
     let seqno = Iq.hi sends in
     let iov = getIov ev in
     Arraye.set s.sends dest (Iq.add sends iov abv) ;
     dn ev abv (Data seqno)
  | _ -> dn ev abv NoHdr
   :
```

Fast-path Optimization with Nuprl

- **Identify Common Case**
  - Events and protocol states of regular communication
  - Formalize as **C**ommon **C**ase **P**redicate



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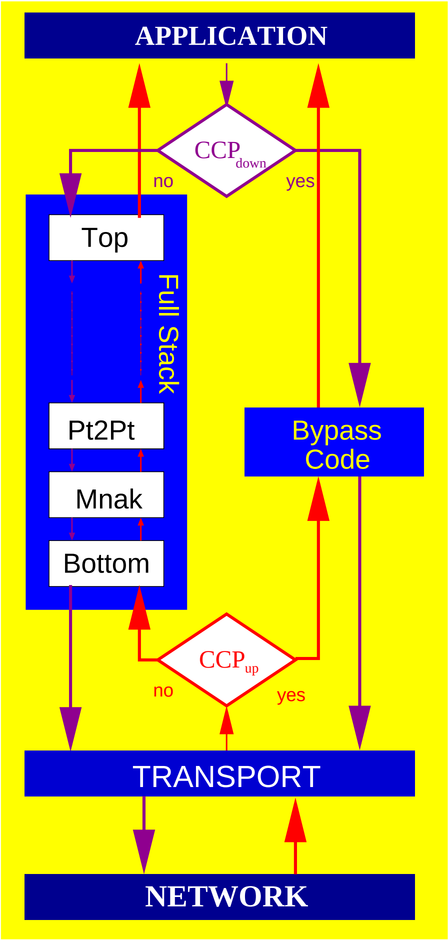

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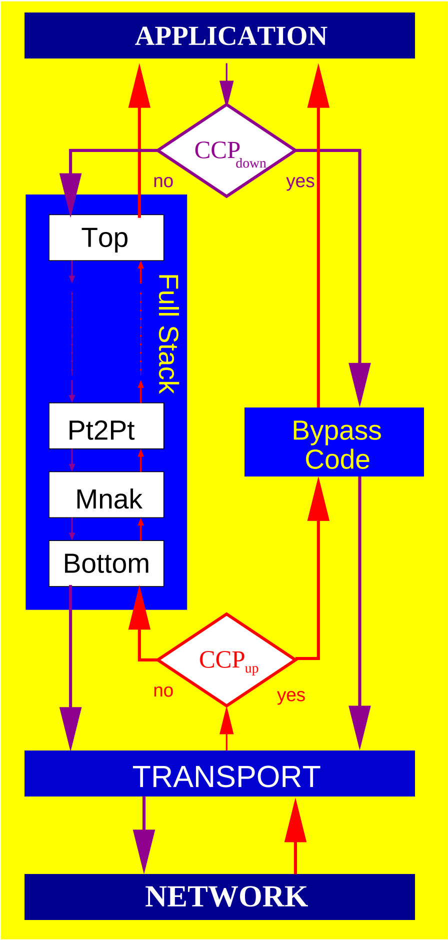

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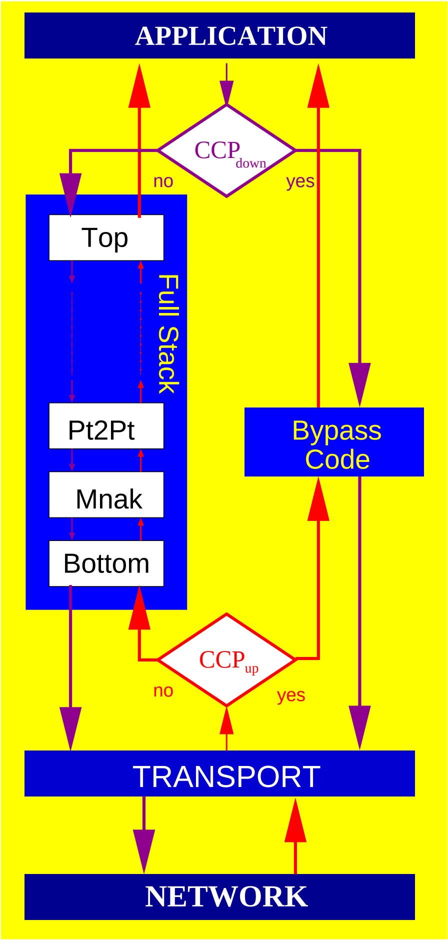

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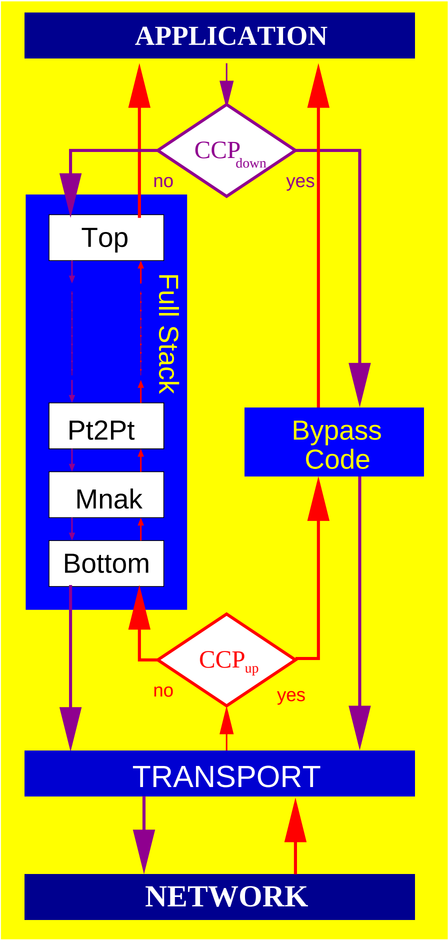

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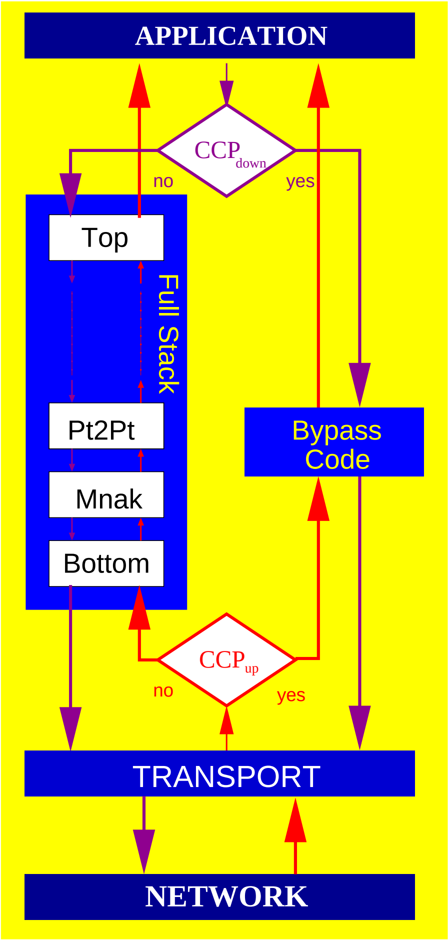
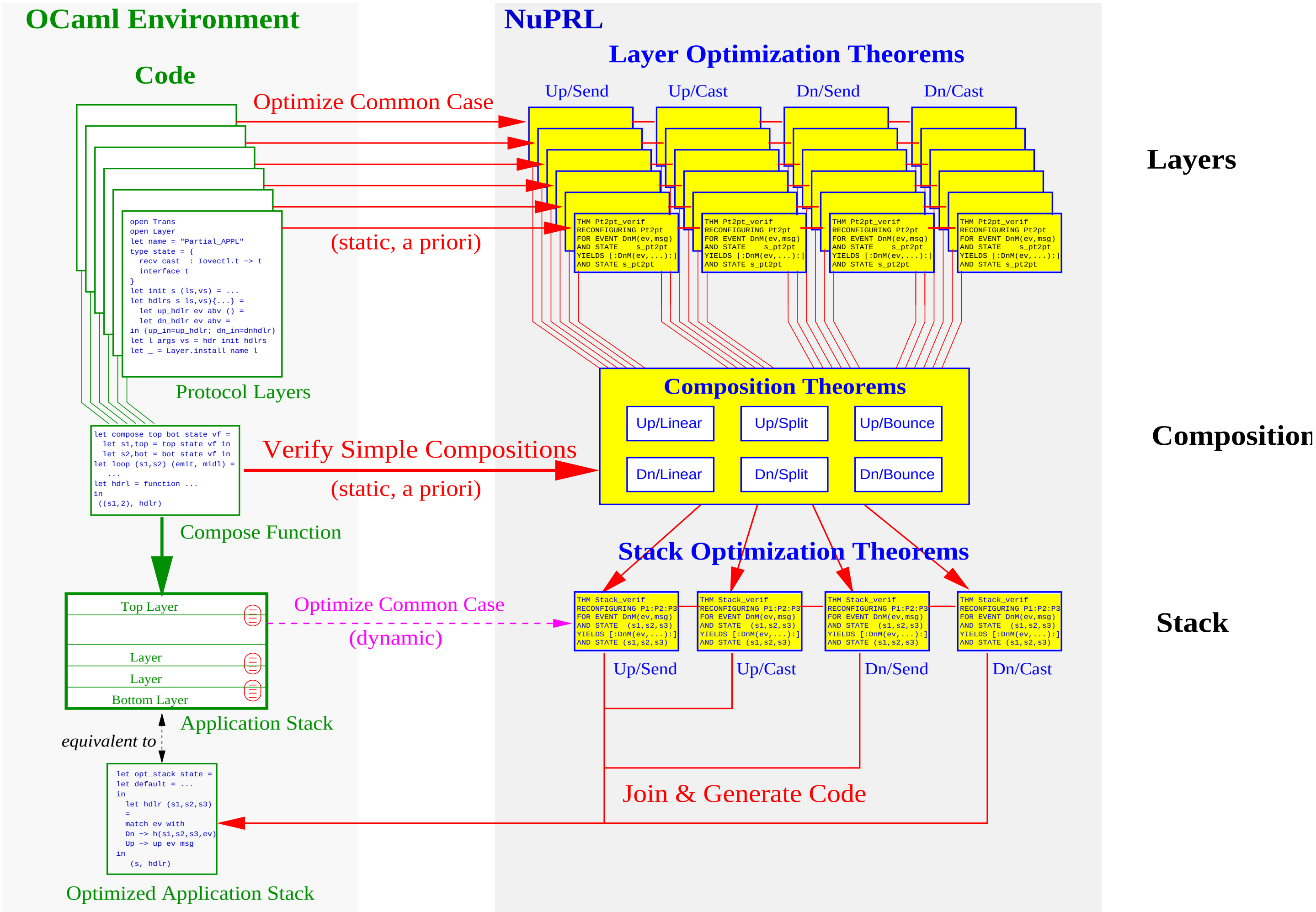


Methodology: compose formal optimization theorems

Fast, error-free, independent of programming language, **speedup factor 3-10**

Methodology: Compose Optimization Theorems



1. Use known optimizations of micro-protocols — A priori: ENSEMBLE + Nuprl experts
2. Compose into optimizations of protocol stacks — automatic: application designer
3. Integrate message header compression — automatic: ⋮
4. Generate code from optimization theorems and reconfigure system — automatic: ⋮

Static optimization of micro protocols

- **A-priori analysis of common execution sequences**
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- **Store result in library as optimization theorem**

```
OPTIMIZING LAYER Pt2pt
       FOR EVENT DnM (ev, msg)
       AND STATE s_pt2pt
        ASSUMING (getType ev) = ESend ∧ not (getPeer ev = ls.rank)
  YIELDS HANDLERS dn ev (Full (Data (Iq.hi
                     (Arraye.get s_pt2pt.sends (getPeer ev))), msg))
     AND UPDATES Iq.add (Arraye.get s_pt2pt.sends (getPeer ev))
                     (getIov ev) msg
```

  - Theorem proves correctness of the local optimization
  - Optimizations of micro protocols part of Ensemble's distribution

Dynamic Optimization of Application Stacks

- **Compose Optimization Theorems**
  - Consult optimization theorems for individual layers
  - Apply composition theorems to generate stack optimization theorems (Linear, simple split, bouncing – send/receive)

```
    OPTIMIZING LAYER Upper
           FOR EVENT DnM(ev, hdr) AND STATE s_up
     YIELDS HANDLERS dn ev msg1 AND UPDATES stmt1
  ∧ OPTIMIZING LAYER Lower
           FOR EVENT DnM(ev, hdr1) AND STATE s_low
     YIELDS HANDLERS dn ev msg2 AND UPDATES stmt2

  ⇒ OPTIMIZING LAYER Upper || Lower
           FOR EVENT DnM(ev, hdr) AND STATE (s_up,s_low)
     YIELDS HANDLERS dn ev msg2 AND UPDATES stmt2; stmt1
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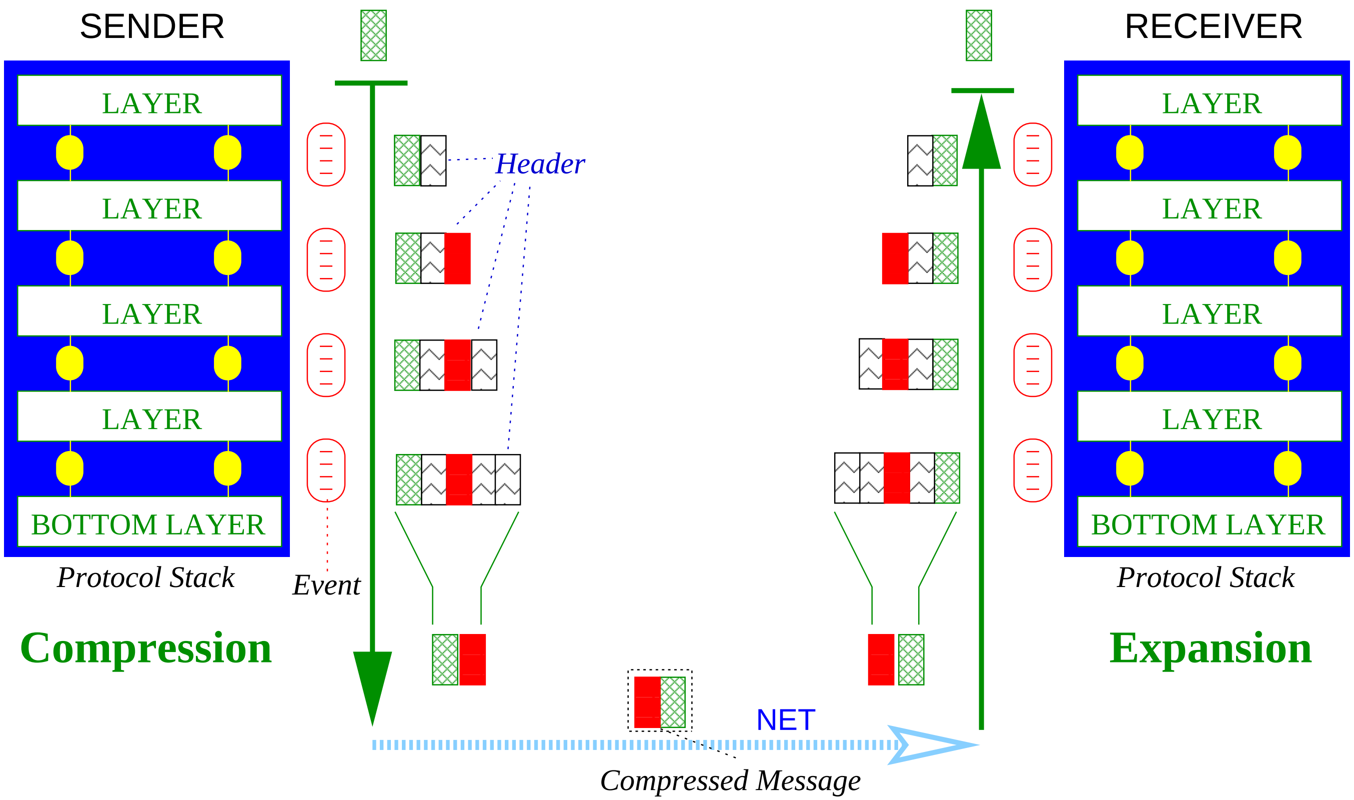
  - Formal proof complex because of complex code for composition
- **Optimization of Protocol Stacks in Linear Time**
  - Use of optimization theorems reduces proof burden for optimizer
  - Pushbutton Technology: requires only configuration of stack

Header compression for fast-path code



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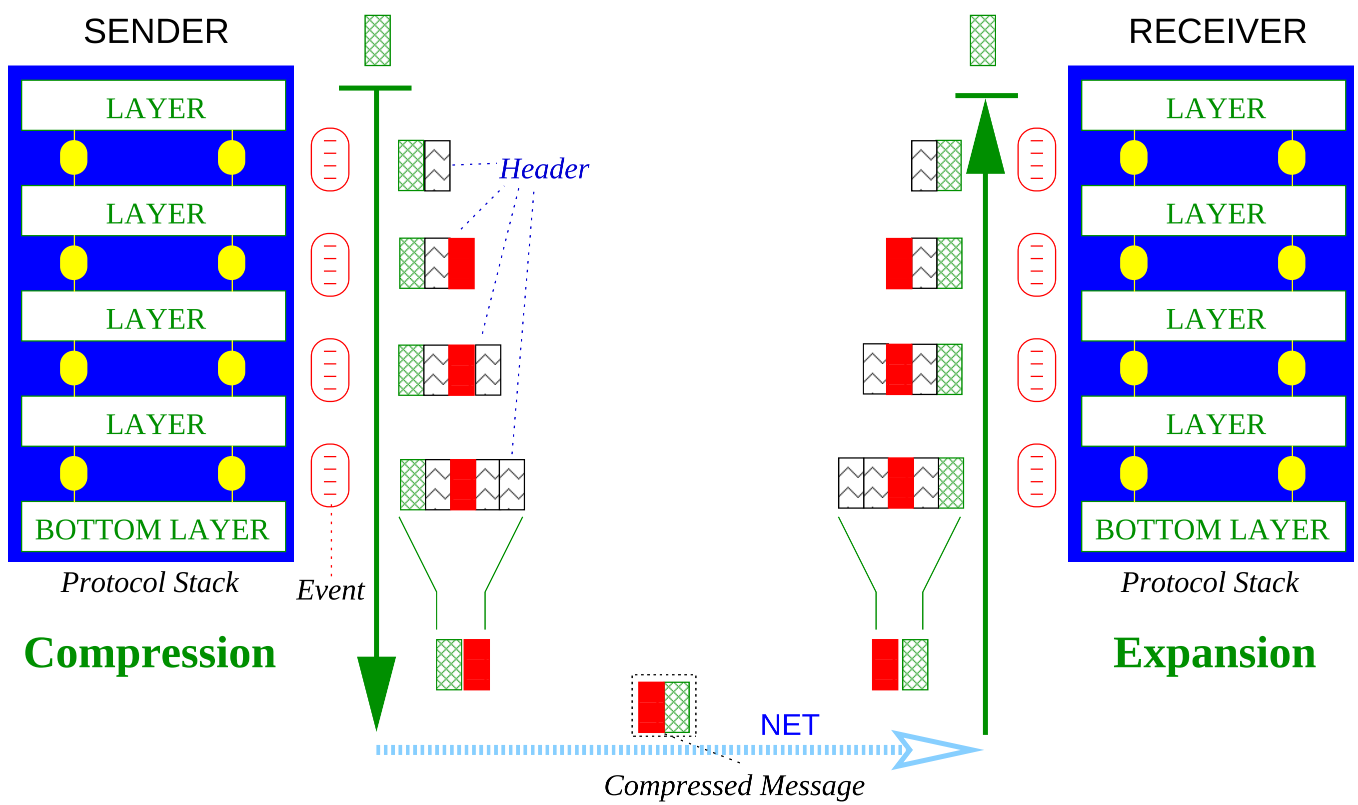

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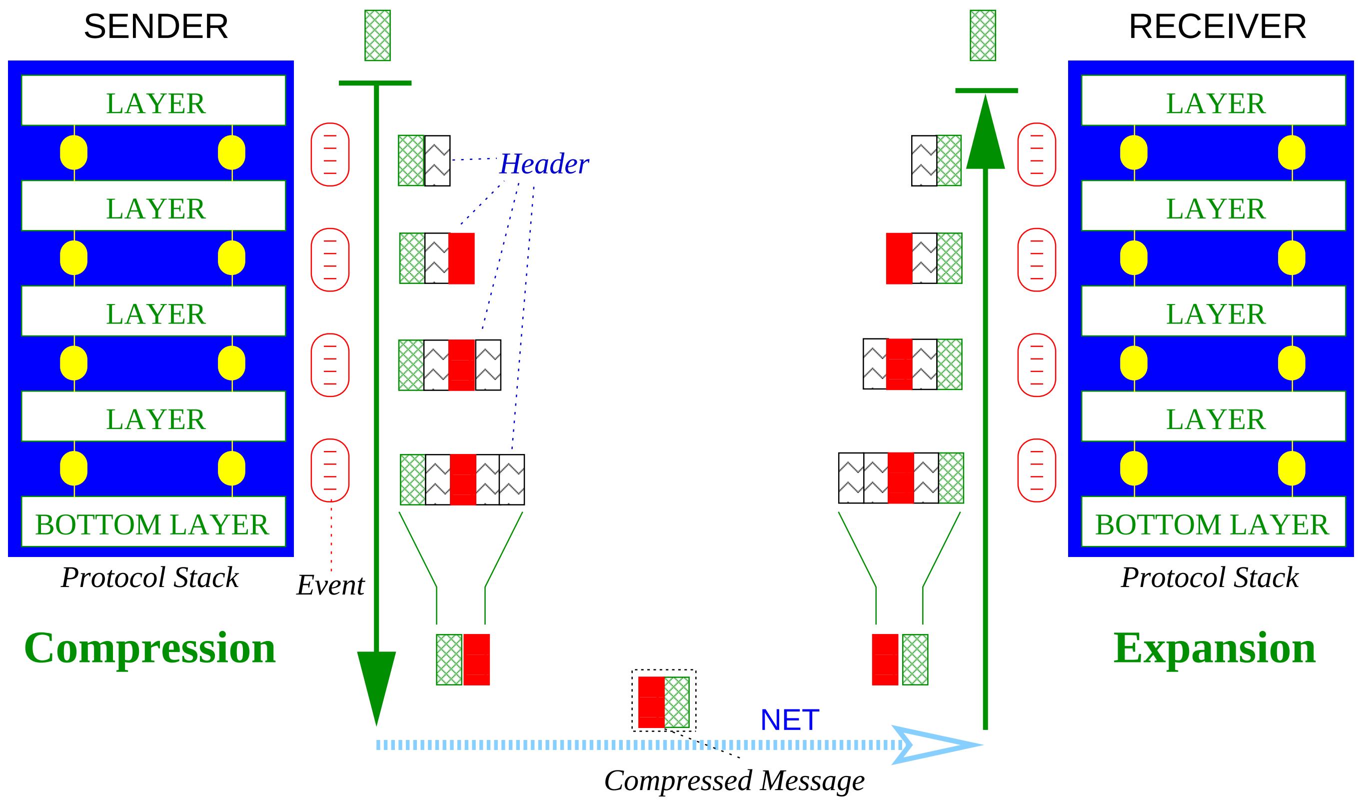

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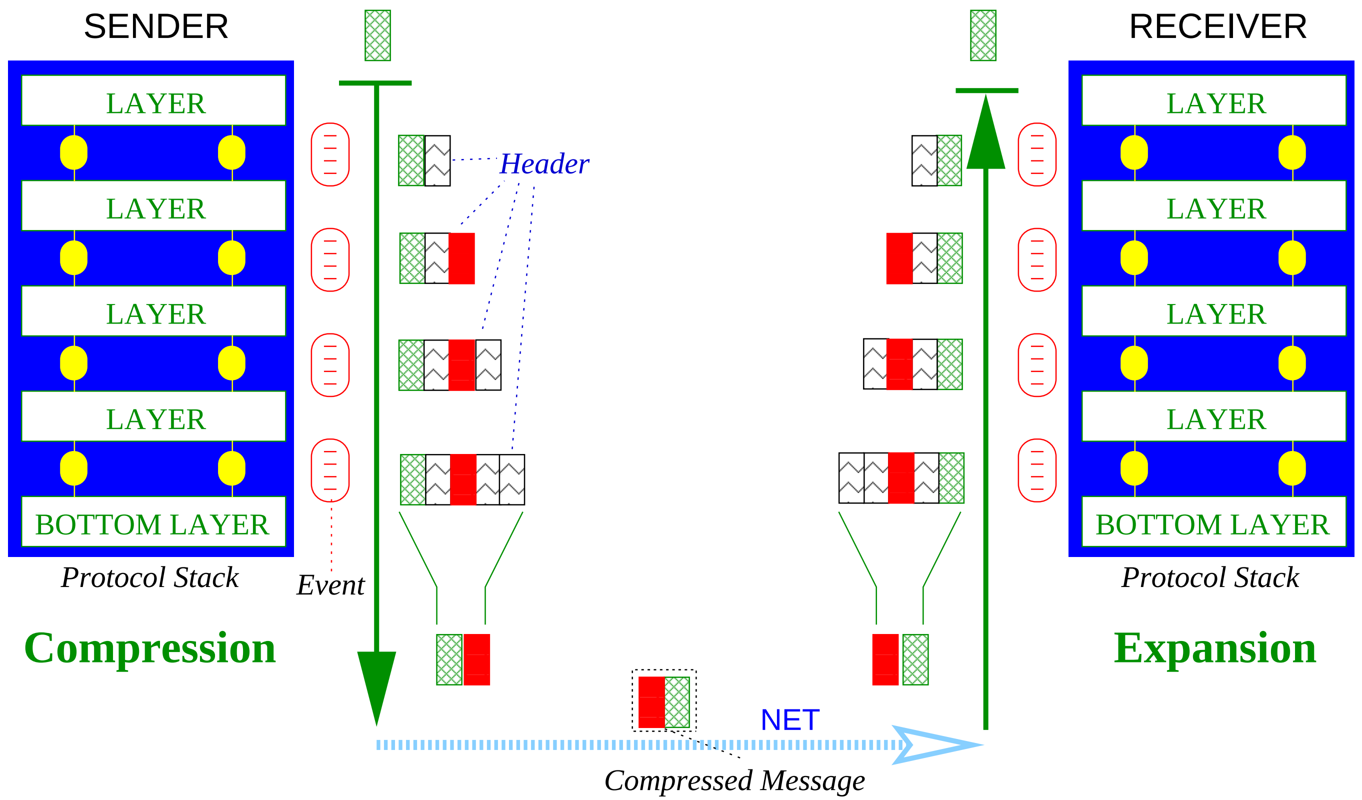

Integrate compression into optimization process

– Generate code for compression and expansion from fast-path headers

– Combine optimization theorem for stack with compression theorems

– Optimized stack uses compressed headers directly

Example Optimization of Bottom::Mnak::Pt2pt

- **Generated optimization theorem for application stack**

```
OPTIMIZING LAYER Pt2pt::Mnak::Bottom
    FOR EVENT    DnM(ev, msg)
    AND STATE    (s_pt2pt, s_mnak, s_bottom)
    ASSUMING     getType ev = ESend ∧ getPeer ev ≠ ls.rank ∧ s_bottom.enabled
 YIELDS HANDLERS dn ev (Full(NoHdr, Full(NoHdr,
                          Full(Data(Iq.hi s_pt2pt.sends.(getPeer ev)),msg))))
    AND UPDATES  Iq.add (Arraye.get s_pt2pt.sends (getPeer ev))(getIov ev) msg
```

- **Generated code for header compression**

```
let compress hdr = match hdr with
   Full(NoHdr, Full(NoHdr, Full(Data(seqno), hdr))) -> OptSend(seqno, hdr)
 | Full(NoHdr, Full(Data(seqno), Full(NoHdr, hdr))) -> OptCast(seqno, hdr)
 | hdr                                              -> Normal(hdr)
```

- **Optimization theorem including header compression**

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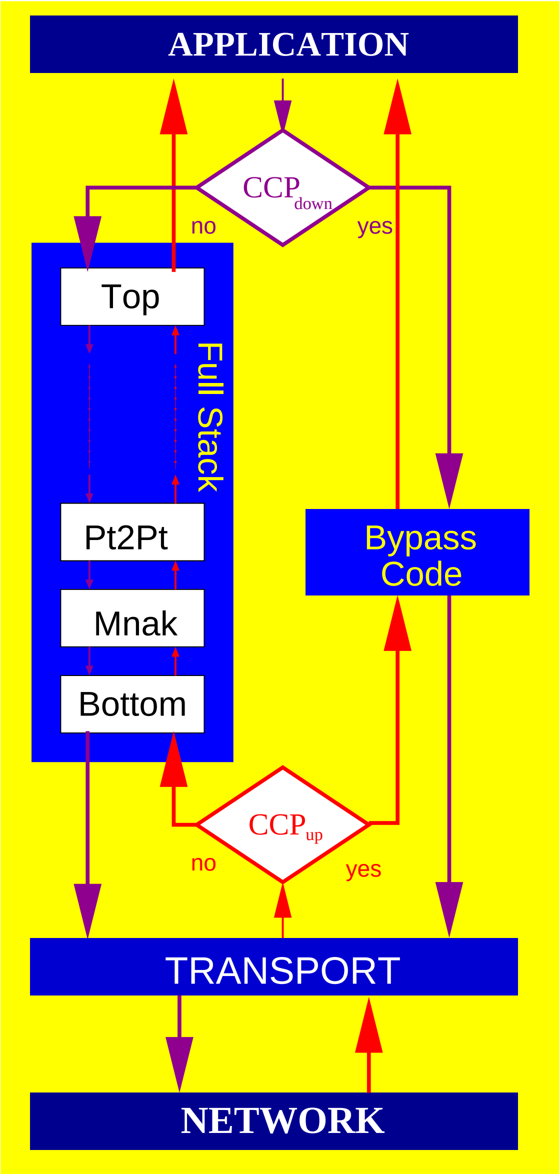
– handlers + updates ↦ command sequence

– CCP ↦ conditional / case-expression

– Call original event handler if CCP fails



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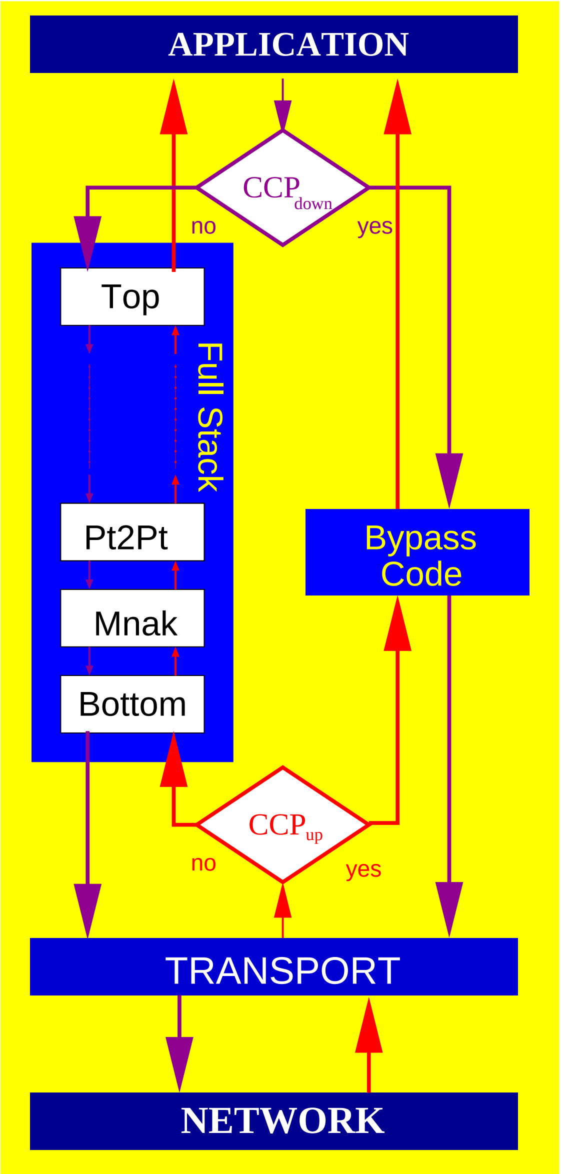

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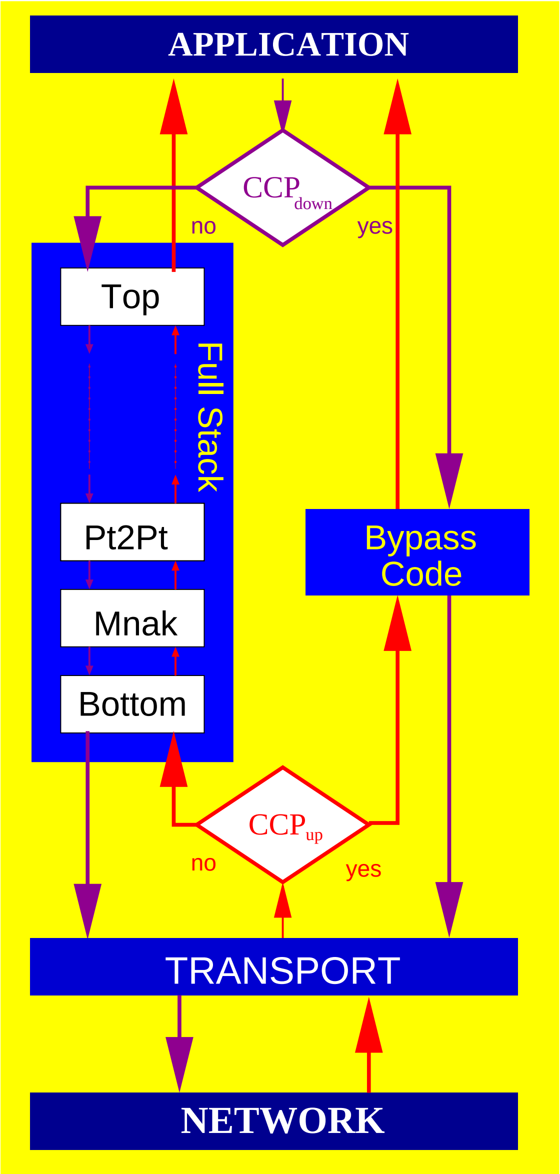

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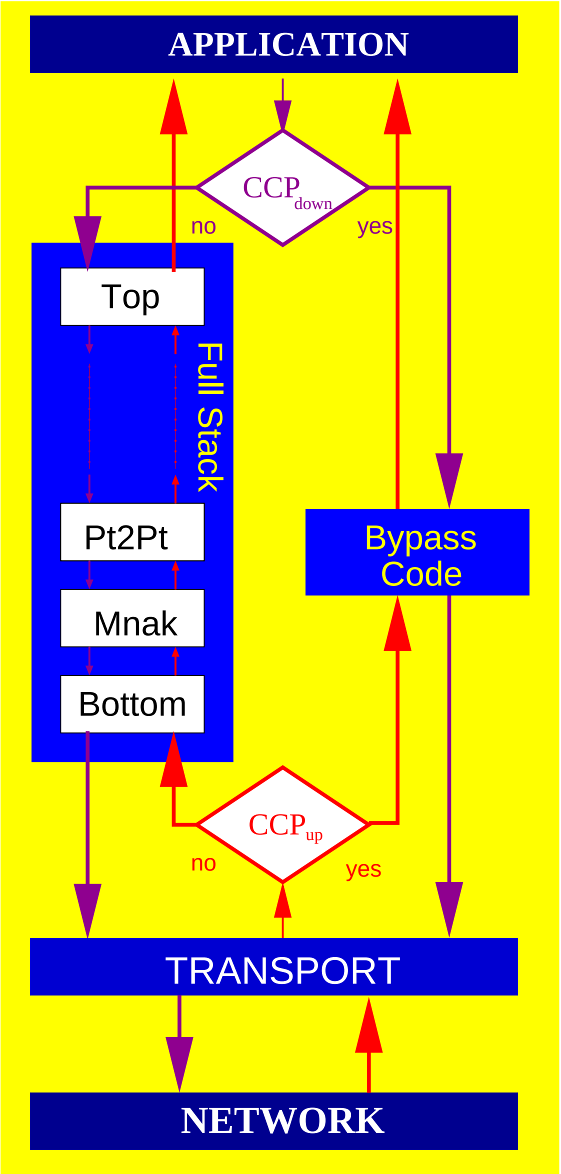
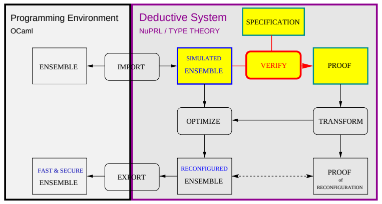
**Fully automated,
generated code 3–10 times faster**



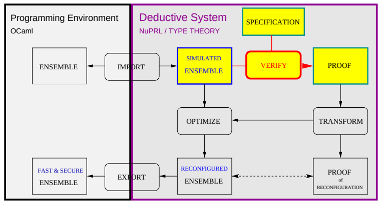


Specifications and Correctness

- **System properties**

  "Messages are received in the same order in which they were sent"

  – Represented in formal mathematics



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  "Messages may be appended to global event queue and removed from its beginning"

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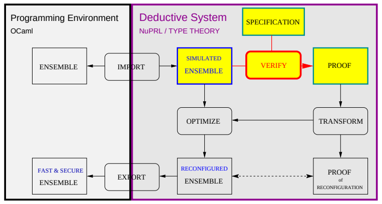

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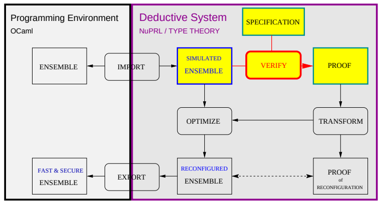

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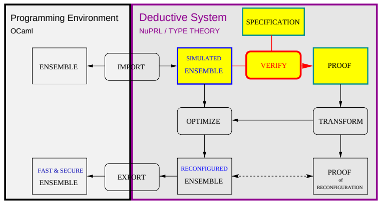

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All formalisms can be represented in Nuprl's type theory

Example specifications of a FIFO network

FIFO property

$\forall$`i,j,k,l<|tr|.(i<j` $\wedge$ `tr[i]`$\downarrow$`tr[k]` $\wedge$ `tr[j]`$\downarrow$`tr[l])` $\Rightarrow$ `k<l`

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Abstract behavioral specification as formal I/O-automaton

Specification	FifoNetwork()	
Variables	in-transit: queue of $\langle Address, Message\rangle$	
Actions	$Send(dst : Address; msg : Message)$	
	condition: true	$\{$in-transit.append($\langle dst, msg\rangle$)$\}$
	$Deliver(dst : Address; msg : Message)$	
	condition: in-transit.head() = $\langle dst, msg\rangle$	$\{$in-transit.dequeue()$\}$

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	condition: in-transit.head() = $\langle dst, msg\rangle$ {in-transit.dequeue()}

Concrete behavioral specification as formal I/O-automaton

Specification	FifoProtocol($p : Address$)
Variables	send-window, recv-window, . . .
Actions	$Above.Send(dst : Address; msg : Message)$
	{ . . . list of individual sub-actions . . . }
	$Below.Send(dst : Address; \langle hdr, msg\rangle : \langle Header, Message\rangle)$
	$Below.Deliver(dst : Address; \langle hdr, msg\rangle : \langle Header, Message\rangle)$
	$Above.Deliver(dst : Address; msg : Message)$
	$Timer()$

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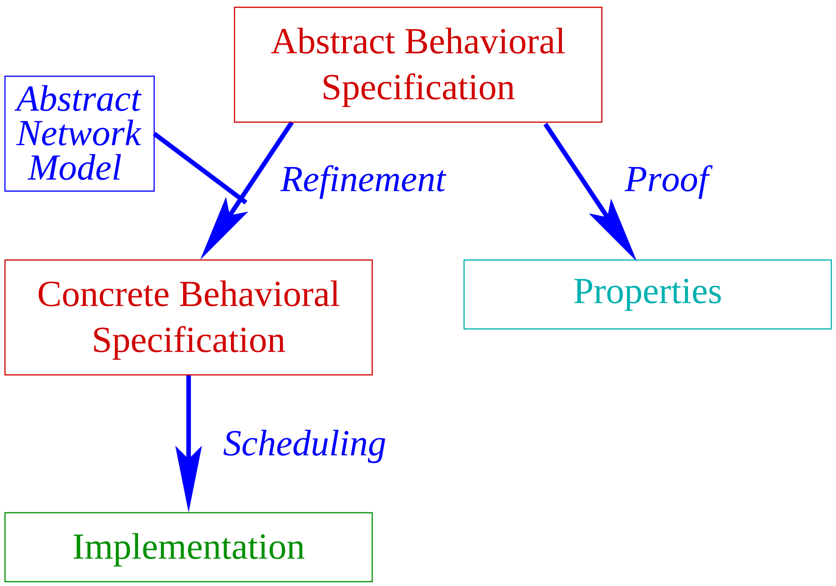
  - Concrete specification $\leftrightarrow$ abstract specification $\rightarrow$ system properties
  - Easy for benign networks $\rightsquigarrow$ **subtle bug discovered**



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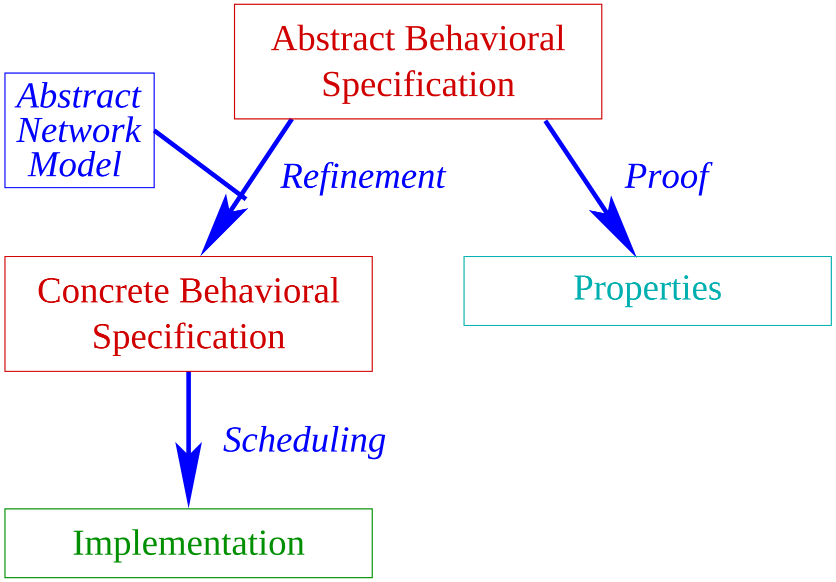

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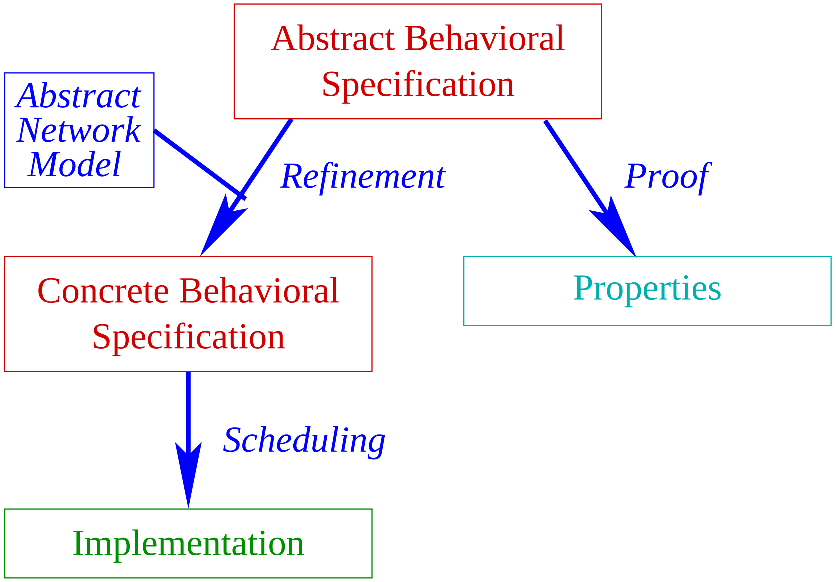

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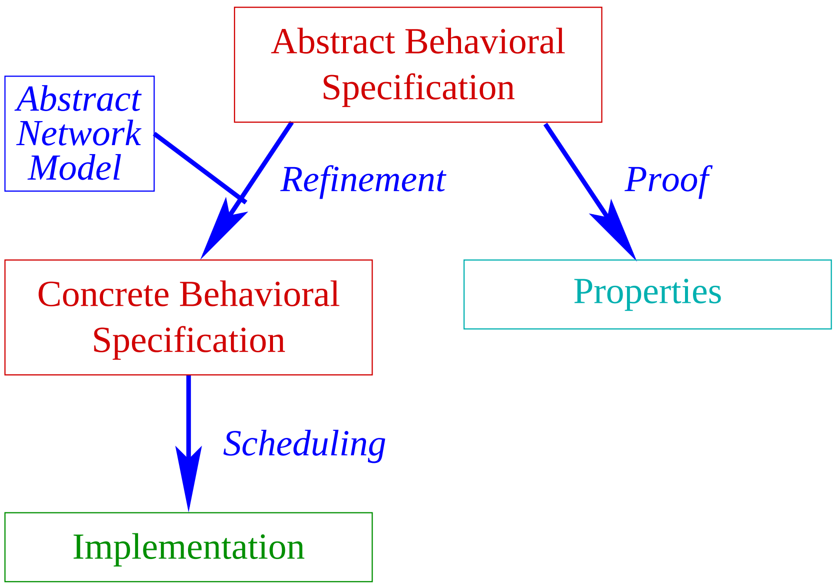
- **Verify code**
  - Micro-protocols ↔ IOA-specifications
  - Layer composition ↔ IOA-composition



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  - Great colleagues! Stuart Allen, Mark Bickford, Ken Birman, Robert Constable, Richard Eaton, Xiaming Liu, Lori Lorigo, Robbert van Renesse

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- **Learn more from applications**
  - Support reasoning about real-time & embedded systems
    - reason about probabilistic protocols
    - reason about end-to-end quality of service
  - Support programming languages with less clean semantics
  - Invert reasoning direction from verification to synthesis

New research issues: Language-based Security

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- **It is about information flow**
  - Simple setting: distinguish high and low confidence levels
  - Secure code will be able to access high-confidence information (h)
  - Modifications of low-confidence data (l) must not depend on h-data

Can we check secure behavior statically by looking at the code?

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Security checkers need precise security models

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