A Concurrent Logical Framework

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(Joint work with Frank Pfenning, David Walker, and Kevin Watkins)

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CLF

- Where it comes from
  - Logical Frameworks
  - The LF approach
- What it is
  - True concurrency
  - Monadic encapsulation
  - A canonical approach
- What next?

All about Logical Frameworks

Represent and reason about object systems

- Languages, logics, …
  - Often semi-formalized as deductive systems
  - Reasoning often informal
- Benefits
  - Formal specification of object system
  - Automate verification of reasoning arguments
  - Feed back into other tools
    - Theorem provers, PCC, …

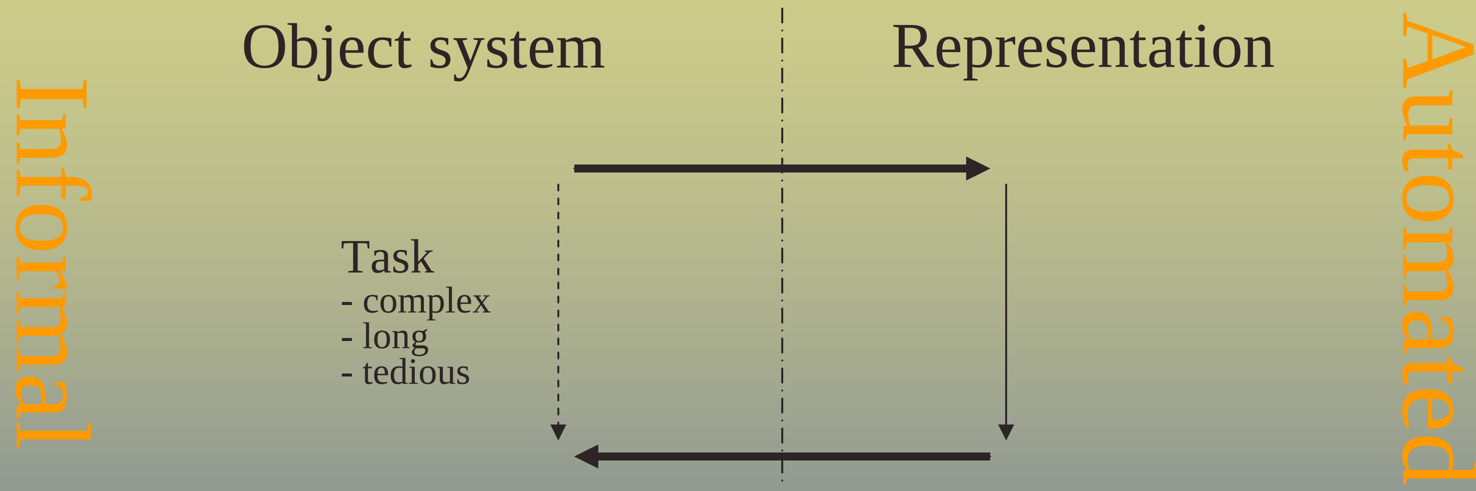
The LF Way

Identify fundamental mechanisms and build them into the framework (soundly!)

- done (right) once and for all instead of each time

- Modular constructions: [Σ-Algebras]
  - *app f a*
- Variable binding, α-renaming, substitution [LF]
  - $\lambda x.\ x+1$
- Disposable, updateable cell [LLF]
  - $\lambda\hat{}s'.\ f\ \hat{}\ s$
- True concurrency [CLF]

It’s all about *Adequacy*



- Adequacy: correctness of the transcription
- LF: make adequacy as simple as possible

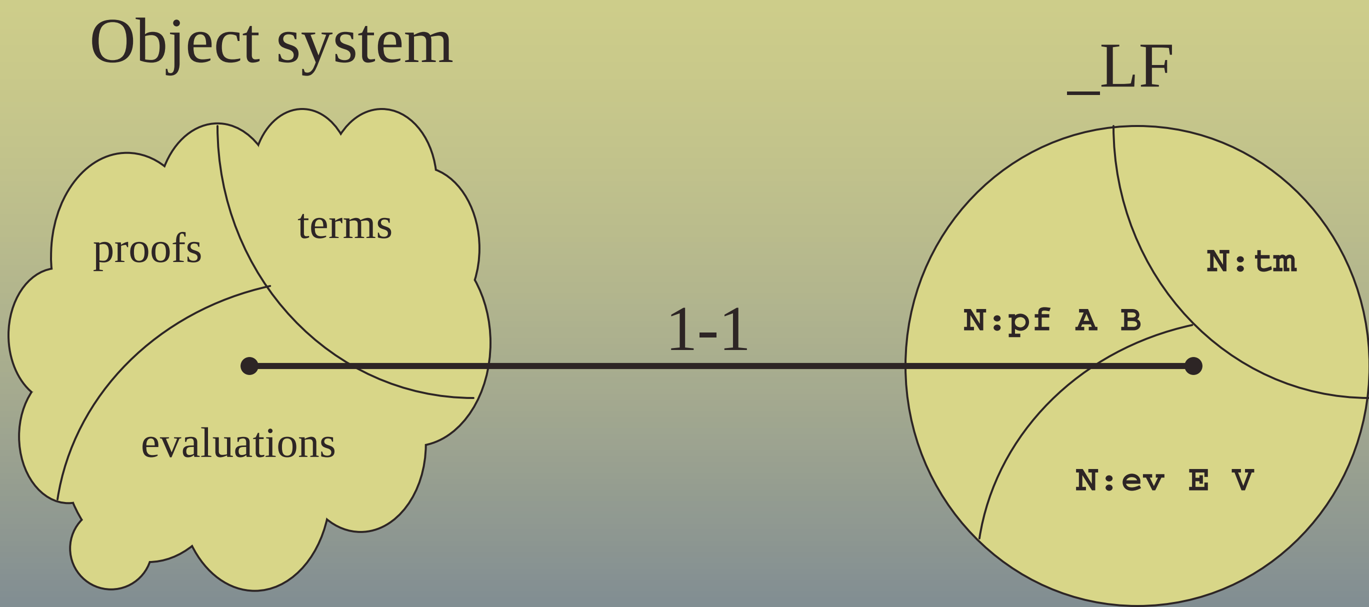
Representation Targets

Mottos, mottos, mottos …

- LF: *judgments-as-types / proofs-as-objects*
  - $\underbrace{3+5 = 8}_{\text{Judgment}} \quad \Rightarrow \quad \underbrace{\texttt{N}}_{\text{object}} \texttt{ : } \underbrace{\texttt{ev (+ 3 5) 8}}_{\text{type}}$

    (a statement we want to make)
- LLF: *state-as-linear-hypotheses / imperative-computations-as-linear-functions*
- CLF: *concurrent-computations-as-monadic-expressions / …*
- nextLF: *blablablablablabla-**as**-blablablablablablablabla / blablablablablablablablabl-**as**-blablablablablabablablablablablabla*

Make it Canonical, Sam



Each object of interest has exactly 1 representation

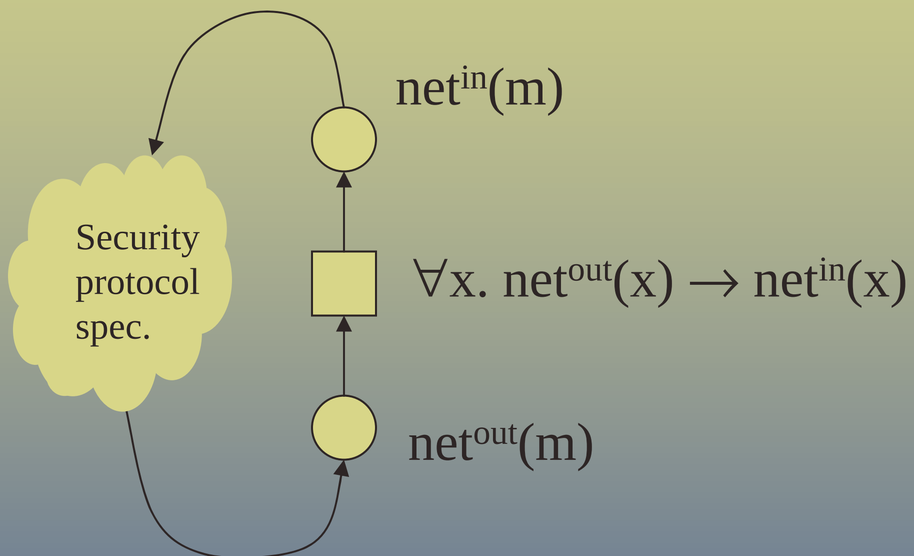
- Canonical objects:
  - η-long, β-normal _LF term
  - Decidable, computable

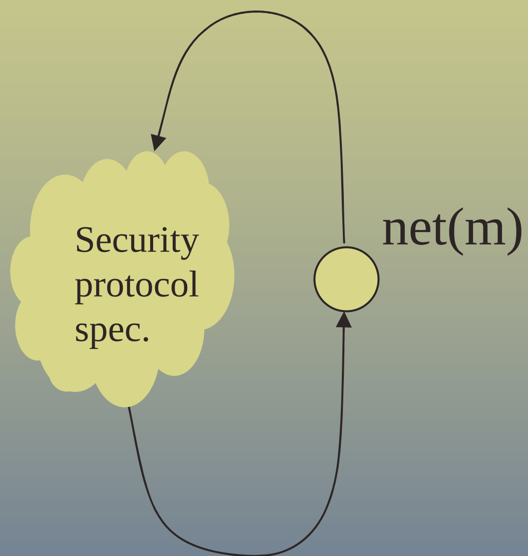
But what is LLF?

- Types (“asynchronous” constructors of ILL)
  - $A ::= a \mid \Pi x{:}A.\, B \mid A \multimap B \mid A \,\&\, B \mid \top$
- Terms
  - $N ::= x \mid \lambda x{:}A.\, N \mid N_1\, N_2$
    $\mid \hat{\lambda} x{:}A.\, N \mid N_1 \hat{}\, N_2 \mid$
    $\langle N_1, N_2 \rangle \mid \mathrm{fst}\, N \mid \mathrm{snd}\, N \mid$
    $\langle\rangle$
- Main judgment
  - $\Gamma ; \Delta \vdash N : A$

CLF

An Example





Many instances can be executing concurrently

LLF Encoding

$\mathtt{net} : \mathit{step} \quad \mathtt{o-}\ \mathtt{net}^{out}\ \mathtt{m}$
$\qquad\qquad\qquad \mathtt{o-}\ (\mathtt{net}^{in}\ \mathtt{m}\ \mathtt{-o}\ \mathit{step}).$

- LLF forces continuation-passing style
- Consider 2 independent applications:
  - $\lambda \mathbf{n}^{i}_{1}.\ \mathtt{net}\ \hat{}\ \mathbf{n}^{o}_{1}\ \hat{}\ (\lambda \mathbf{n}^{i}_{2}.\ \mathtt{net}\ \hat{}\ \mathbf{n}^{o}_{2}\ \hat{}\ \mathtt{C})$
  - $\lambda \mathbf{n}^{i}_{2}.\ \mathtt{net}\ \hat{}\ \mathbf{n}^{o}_{2}\ \hat{}\ (\lambda \mathbf{n}^{i}_{1}.\ \mathtt{net}\ \hat{}\ \mathbf{n}^{o}_{1}\ \hat{}\ \mathtt{C})$

  Should be indistinguishable (***true concurrency***)
- Equate them at the meta-level

  $\mathtt{same\text{-}trace}\ \mathtt{T}_1\ \mathtt{T}_2\ \mathtt{o-}\ \ldots$

  Never-ending even for small system!

Encoding in Linear logic

$$\forall m.\ net^{out}\ m\ \multimap\ net^{in}\ m$$

- <u>Much</u> simpler
- In general, requires "synchronous" operators
  - $\otimes$ and **1**
- Concurrency given by "commuting conversions"

$$\begin{aligned} & \text{let } x_1 \otimes y_1 = N_1 \text{ in } (\text{let } x_2 \otimes y_2 = N_2 \text{ in } M) \\ = \ & \text{let } x_2 \otimes y_2 = N_2 \text{ in } (\text{let } x_1 \otimes y_1 = N_1 \text{ in } M) \qquad \text{if } x_i, y_i \notin FV(R_{2\text{-}i}) \end{aligned}$$

- … looks like what we want …

However …

- Commuting conversions are too wild
  - Allow permutations we don't care for

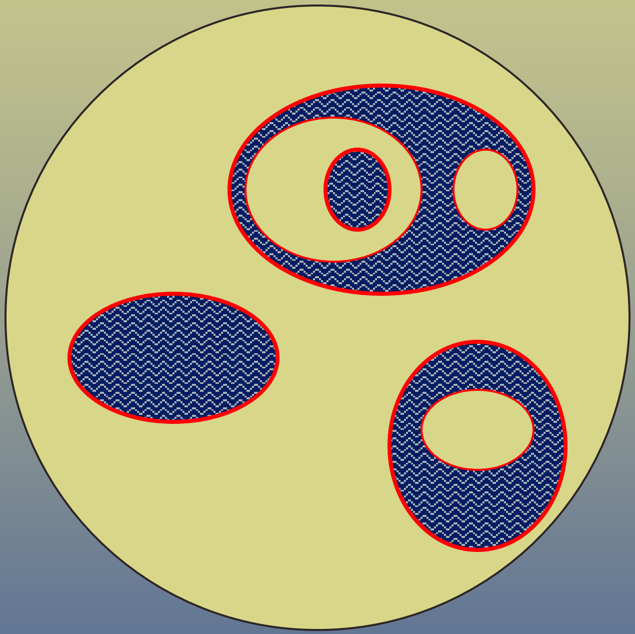
- Synchronous types destroy uniqueness of canonical forms
  - **`nat:type.   z:nat.   s:nat->nat.   c:1.`**
  - Natural numbers: **`z`**, **`s z`**, **`s`** (**`s z`**), …
  - What about **`let 1 = c in z`** ? What if **`c`** is linear?

- No good! ☹

Monadic Encapsulation

Separate synchronous and asynchronous types

- *Outside* the monad
  - LLF types (asynchronous)
  - η-long, β-normal forms
- *Inside* the monad
  - Synchronous types
  - Commuting conversions
    - *Concurrency equation*
  - η-long, β-normal forms
- Monad is a sandbox for synchronous behavior



CLF

- Types
  - $A ::= a \mid \Pi\, x{:}A.\ B \mid A \multimap B \mid A \mathbin{\&} B \mid \top \mid \{S\}$
  - $S ::= A \mid\ !A \mid S_1 \otimes S_2 \mid \mathbf{1} \mid \exists x{:}A.\ S$
- Terms
  - $N ::= x \mid \lambda\, x{:}A.\ N \mid N_1\ N_2 \mid \lambda\hat{}x{:}A.\ N \mid N_1\hat{}N_2 \mid <N_1,N_2> \mid \mathrm{fst}\ N \mid \mathrm{snd}\ N \mid <> \mid \{E\}$
  - $E ::= M \mid \mathrm{let}\ \{p\} = N\ \mathrm{in}\ E$
  - $M ::= N \mid\ !N \mid M_1 \otimes M_2 \mid 1 \mid [N,M]$
  - $p ::= x \mid\ !x \mid p_1 \otimes p_2 \mid 1 \mid [x,p]$

Example in CLF

$$\mathtt{net\ :\ net^{in}\ m\ {-o}\ \{\ net^{out}\ m\ \}.}$$

- Relating the 2 specifications
  - 2 sets of CLF declarations
  - Meta-level definition of trace transformation

    $$\mathtt{simplify\text{-}net\ \{T^{i/o}\}\ \{T\}}$$

    - Trivial mapping
    - Permutations handled automatically
      - No need to take action
      - Critical for more complex examples

The Canonical Approach

_LF meta-theory:

- Decidability of type-checking
  - Existence of unique canonical forms
  - Substitution theorem, …

A progression of techniques

- LF: start with equality modulo β, η over all terms
  - ~10 years to prove [several Ph.D. theses, book]
- LLF: start with equality modulo β over η-long terms
  - ~6 months to prove [thesis]
- CLF: work only with η-long, β-normal terms
  - ~2 weeks to prove [method is the thesis]
  - Applicable with minimal effort to other languages

Examples and Applications

- π-calculus
  - Synchronous
  - Asynchronous
- Concurrent ML
- Petri nets
  - Execution-sequence semantics
  - Trace semantics
- MSR security protocol specification language

- No implementation … yet …

Further Reading

- Watkins, Cervesato, Pfenning, Walker: *A Concurrent Logical Framework: the Propositional Case*, Oct. 2002
- CPWW: *A Concurrent Logical Framework*, Jan. 2002
- Forthcoming technical reports
  - *A Concurrent Logical Framework I: Judgments and Properties*
  - *A Concurrent Logical Framework II: Examples and Applications*
- NOT the paper in the proceedings

What Next?

Future Work

- Further development
  - Appropriate operational semantics
  - Irrelevant types
  - Multiple monads, …
- Further experience
  - More concurrent systems
    - Process algebras
    - Security protocols, …
  - Reasoning
    - Trace-base reasoning
    - Process equivalences, …

Conclusions

CLF

- A logical framework that internalizes true concurrency
- Monadic encapsulation tames commuting conversions
- Canonical approach to meta-theory
- Good number of examples

- *This is just the beginning … plenty more to do!*