

Foundations of Software Fall 2021

Week 6

Plan

PREVIOUSLY:

1. type safety as *progress* and *preservation*
2. typed arithmetic expressions
3. simply typed lambda calculus (STLC)

TODAY:

1. Equivalence of lambda terms
2. Preservation for STLC
3. Extensions to STLC

NEXT: state, exceptions

NEXT: polymorphic (not so simple) typing

Equivalence of Lambda Terms

Representing Numbers

We have seen how certain terms in the lambda-calculus can be used to represent natural numbers.

$$c_0 = \lambda s. \lambda z. z$$

$$c_1 = \lambda s. \lambda z. s \ z$$

$$c_2 = \lambda s. \lambda z. s \ (s \ z)$$

$$c_3 = \lambda s. \lambda z. s \ (s \ (s \ z))$$

Other lambda-terms represent common operations on numbers:

$$scc = \lambda n. \lambda s. \lambda z. s \ (n \ s \ z)$$

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$$c_3 = \lambda s. \lambda z. s \ (s \ (s \ z))$$

Other lambda-terms represent common operations on numbers:

$$scc = \lambda n. \lambda s. \lambda z. s \ (n \ s \ z)$$

In what sense can we say this representation is “correct”?

In particular, on what basis can we argue that `scc` on church numerals corresponds to ordinary successor on numbers?

The naive approach

One possibility:

For each n , the term $scc\ c_n$ evaluates to c_{n+1} .

The naive approach... doesn't work

One possibility:

For each n , the term $scc\ c_n$ evaluates to c_{n+1} .

Unfortunately, this is false.

E.g.:

$$\begin{aligned}scc\ c_2 &= (\lambda n. \lambda s. \lambda z. s\ (n\ s\ z))\ (\lambda s. \lambda z. s\ (s\ z)) \\&\longrightarrow \lambda s. \lambda z. s\ ((\lambda s. \lambda z. s\ (s\ z))\ s\ z) \\&\neq \lambda s. \lambda z. s\ (s\ (s\ z)) \\&= c_3\end{aligned}$$

A better approach

Recall the intuition behind the church numeral representation:

- ▶ a number n is represented as a term that “does something n times to something else”
- ▶ `scc` takes a term that “does something n times to something else” and returns a term that “does something $n + 1$ times to something else”

I.e., what we really care about is that `scc c2` behaves the same as `c3` when applied to two arguments.

$$\begin{aligned}
\text{SCC } c_2 \ v \ w &= (\lambda n. \ \lambda s. \ \lambda z. \ s \ (n \ s \ z)) \ (\lambda s. \ \lambda z. \ s \ (s \ z)) \ v \ w \\
&\longrightarrow (\lambda s. \ \lambda z. \ s \ ((\lambda s. \ \lambda z. \ s \ (s \ z)) \ s \ z)) \ v \ w \\
&\longrightarrow (\lambda z. \ v \ ((\lambda s. \ \lambda z. \ s \ (s \ z)) \ v \ z)) \ w \\
&\longrightarrow v \ ((\lambda s. \ \lambda z. \ s \ (s \ z)) \ v \ w) \\
&\longrightarrow v \ ((\lambda z. \ v \ (v \ z)) \ w) \\
&\longrightarrow v \ (v \ (v \ w))
\end{aligned}$$

$$\begin{aligned}
c_3 \ v \ w &= (\lambda s. \ \lambda z. \ s \ (s \ (s \ z))) \ v \ w \\
&\longrightarrow (\lambda z. \ v \ (v \ (v \ z))) \ w \\
&\longrightarrow v \ (v \ (v \ w))
\end{aligned}$$

A general question

We have argued that, although $\text{scc } c_2$ and c_3 do not evaluate to the same thing, they are nevertheless “behaviorally equivalent.”

What, precisely, does behavioral equivalence mean?

Intuition

Roughly,

“terms s and t are behaviorally equivalent”

should mean:

“there is no ‘test’ that distinguishes s and t — i.e., no way to put them in the same context and observe different results.”

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To make this precise, we need to be clear what we mean by a *testing context* and how we are going to *observe* the results of a test.

Examples

```
tru = λt. λf. t
tru' = λt. λf. (λx.x) t
fls = λt. λf. f
omega = (λx. x x) (λx. x x)
poisonpill = λx. omega
placebo = λx. tru
Yf = (λx. f (x x)) (λx. f (x x))
```

Which of these are behaviorally equivalent?

Observational equivalence

As a first step toward defining behavioral equivalence, we can use the notion of *normalizability* to define a simple notion of *test*.

Two terms s and t are said to be *observationally equivalent* if either both are normalizable (i.e., they reach a normal form after a finite number of evaluation steps) or both diverge.

I.e., we “observe” a term’s behavior simply by running it and seeing if it halts.

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Aside:

- ▶ Is observational equivalence a decidable property?

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I.e., we “observe” a term’s behavior simply by running it and seeing if it halts.

Aside:

- ▶ Is observational equivalence a decidable property?
- ▶ Does this mean the definition is ill-formed?

Examples

- ▶ `omega` and `tru` are *not* observationally equivalent

Examples

- ▶ `omega` and `tru` are *not* observationally equivalent
- ▶ `tru` and `fls` are observationally equivalent

Behavioral Equivalence

This primitive notion of observation now gives us a way of “testing” terms for behavioral equivalence

Terms s and t are said to be *behaviorally equivalent* if, for every finite sequence of values v_1, v_2, \dots, v_n , the applications

$$s \ v_1 \ v_2 \ \dots \ v_n$$

and

$$t \ v_1 \ v_2 \ \dots \ v_n$$

are observationally equivalent.

Examples

These terms are behaviorally equivalent:

```
tru =  $\lambda t. \lambda f. t$   
tru' =  $\lambda t. \lambda f. (\lambda x. x) t$ 
```

So are these:

```
omega =  $(\lambda x. x x) (\lambda x. x x)$   
 $Y_f = (\lambda x. f (x x)) (\lambda x. f (x x))$ 
```

These are not behaviorally equivalent (to each other, or to any of the terms above):

```
fls =  $\lambda t. \lambda f. f$   
poisonpill =  $\lambda x. \text{omega}$   
placebo =  $\lambda x. \text{tru}$ 
```

Proving behavioral equivalence

Given terms s and t , how do we *prove* that they are (or are not) behaviorally equivalent?

Proving behavioral inequivalence

To prove that s and t are *not* behaviorally equivalent, it suffices to find a sequence of values $v_1 \dots v_n$ such that one of

$$s \ v_1 \ v_2 \ \dots \ v_n$$

and

$$t \ v_1 \ v_2 \ \dots \ v_n$$

diverges, while the other reaches a normal form.

Proving behavioral inequivalence

Example:

- ▶ the single argument `unit` demonstrates that `fls` is not behaviorally equivalent to `poisonpill`:

$$\begin{aligned} & \text{fls unit} \\ = & (\lambda t. \lambda f. f) \text{ unit} \\ & \longrightarrow^* \lambda f. f \end{aligned}$$

`poisonpill unit`
diverges

Proving behavioral inequivalence

Example:

- ▶ the argument sequence $(\lambda x. x) \text{ poisonpill } (\lambda x. x)$ demonstrate that `tru` is not behaviorally equivalent to `fls`:

$$\begin{aligned} & \text{tru } (\lambda x. x) \text{ poisonpill } (\lambda x. x) \\ & \quad \longrightarrow^* (\lambda x. x)(\lambda x. x) \\ & \quad \longrightarrow^* \lambda x. x \end{aligned}$$
$$\begin{aligned} & \text{fls } (\lambda x. x) \text{ poisonpill } (\lambda x. x) \\ & \longrightarrow^* \text{poisonpill } (\lambda x. x), \text{ which diverges} \end{aligned}$$

Proving behavioral equivalence

To prove that s and t are behaviorally equivalent, we have to work harder: we must show that, for every sequence of values $v_1 \dots v_n$, either both

$s \ v_1 \ v_2 \ \dots \ v_n$

and

$t \ v_1 \ v_2 \ \dots \ v_n$

diverge, or else both reach a normal form.

How can we do this?

Proving behavioral equivalence

In general, such proofs require some additional machinery that we will not have time to get into in this course (so-called *applicative bisimulation*). But, in some cases, we can find simple proofs.

Theorem: These terms are behaviorally equivalent:

$$\begin{aligned}\text{tru} &= \lambda t. \lambda f. t \\ \text{tru}' &= \lambda t. \lambda f. (\lambda x. x) t\end{aligned}$$

Proof: Consider an arbitrary sequence of values $v_1 \dots v_n$.

- ▶ For the case where the sequence has just one element (i.e., $n = 1$), note that both $\text{tru } v_1$ and $\text{tru}' v_1$ reach normal forms after one reduction step.
- ▶ For the case where the sequence has more than one element (i.e., $n > 1$), note that both $\text{tru } v_1 v_2 v_3 \dots v_n$ and $\text{tru}' v_1 v_2 v_3 \dots v_n$ reduce (in two steps) to $v_1 v_3 \dots v_n$. So either both normalize or both diverge.

Proving behavioral equivalence

Theorem: These terms are behaviorally equivalent:

$$\begin{aligned}\text{omega} &= (\lambda x. x x) (\lambda x. x x) \\ Y_f &= (\lambda x. f (x x)) (\lambda x. f (x x))\end{aligned}$$

Proof: Both

$$\text{omega } v_1 \dots v_n$$

and

$$Y_f v_1 \dots v_n$$

diverge, for every sequence of arguments $v_1 \dots v_n$.

Preservation for STLC

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Theorem: If $\Gamma \vdash t : T$ and $t \longrightarrow t'$, then $\Gamma \vdash t' : T$.

Proof: By induction

Preservation for STLC

Theorem: If $\Gamma \vdash t : T$ and $t \longrightarrow t'$, then $\Gamma \vdash t' : T$.

Proof: By induction on typing derivations.

Which case is the hard one??

Preservation for STLC

Theorem: If $\Gamma \vdash t : T$ and $t \longrightarrow t'$, then $\Gamma \vdash t' : T$.

Proof: By induction on typing derivations.

Case T-APP: Given $t = t_1 \ t_2$
 $\Gamma \vdash t_1 : T_{11} \rightarrow T_{12}$
 $\Gamma \vdash t_2 : T_{11}$
 $T = T_{12}$
Show $\Gamma \vdash t' : T_{12}$

Preservation for STLC

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By the inversion lemma for evaluation, there are three subcases...

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$$\begin{aligned} t &= t_1 \ t_2 \\ \Gamma \vdash t_1 &: T_{11} \rightarrow T_{12} \\ \Gamma \vdash t_2 &: T_{11} \\ T &= T_{12} \end{aligned}$$

Show $\Gamma \vdash t' : T_{12}$

By the inversion lemma for evaluation, there are three subcases...

Subcase:

$$\begin{aligned} t_1 &= \lambda x:T_{11}. \ t_{12} \\ t_2 &\text{ a value } v_2 \\ t' &= [x \mapsto v_2]t_{12} \end{aligned}$$

Preservation for STLC

Theorem: If $\Gamma \vdash t : T$ and $t \longrightarrow t'$, then $\Gamma \vdash t' : T$.

Proof: By induction on typing derivations.

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Show $\Gamma \vdash t' : T_{12}$

By the inversion lemma for evaluation, there are three subcases...

Subcase: $t_1 = \lambda x:T_{11}. t_{12}$
 t_2 a value v_2
 $t' = [x \mapsto v_2]t_{12}$

Uh oh.

The “Substitution Lemma”

Lemma: Types are preserved under substitution.

That is, if $\Gamma, x:S \vdash t : T$ and $\Gamma \vdash s : S$, then $\Gamma \vdash [x \mapsto s]t : T$.

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Proof: ...

Weakening and Permutation

Two other lemmas will be useful.

Weakening tells us that we can *add assumptions* to the context without losing any true typing statements.

Lemma: If $\Gamma \vdash t : T$ and $x \notin \text{dom}(\Gamma)$, then $\Gamma, x:S \vdash t : T$.

Weakening and Permutation

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Permutation tells us that the order of assumptions in (the list) Γ does not matter.

Lemma: If $\Gamma \vdash t : T$ and Δ is a permutation of Γ , then $\Delta \vdash t : T$.

Weakening and Permutation

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Lemma: If $\Gamma \vdash t : T$ and $x \notin \text{dom}(\Gamma)$, then $\Gamma, x:S \vdash t : T$.

Moreover, the latter derivation has the same depth as the former.

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Lemma: If $\Gamma \vdash t : T$ and Δ is a permutation of Γ , then $\Delta \vdash t : T$.

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The “Substitution Lemma”

Lemma: If $\Gamma, x:S \vdash t : T$ and $\Gamma \vdash s : S$, then $\Gamma \vdash [x \mapsto s]t : T$.

I.e., “Types are preserved under substitution.”

The “Substitution Lemma”

Lemma: If $\Gamma, x:S \vdash t : T$ and $\Gamma \vdash s : S$, then $\Gamma \vdash [x \mapsto s]t : T$.

Proof: By induction on the derivation of $\Gamma, x:S \vdash t : T$. Proceed by cases on the final typing rule used in the derivation.

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Case T-APP: $t = t_1 \ t_2$
 $\Gamma, x:S \vdash t_1 : T_2 \rightarrow T_1$
 $\Gamma, x:S \vdash t_2 : T_2$
 $T = T_1$

By the induction hypothesis, $\Gamma \vdash [x \mapsto s]t_1 : T_2 \rightarrow T_1$ and $\Gamma \vdash [x \mapsto s]t_2 : T_2$. By T-APP, $\Gamma \vdash [x \mapsto s]t_1 \ [x \mapsto s]t_2 : T$, i.e., $\Gamma \vdash [x \mapsto s](t_1 \ t_2) : T$.

The “Substitution Lemma”

Lemma: If $\Gamma, x:S \vdash t : T$ and $\Gamma \vdash s : S$, then $\Gamma \vdash [x \mapsto s]t : T$.

Proof: By induction on the derivation of $\Gamma, x:S \vdash t : T$. Proceed by cases on the final typing rule used in the derivation.

Case T-VAR: $t = z$
with $z:T \in (\Gamma, x:S)$

There are two sub-cases to consider, depending on whether z is x or another variable. If $z = x$, then $[x \mapsto s]z = s$. The required result is then $\Gamma \vdash s : S$, which is among the assumptions of the lemma. Otherwise, $[x \mapsto s]z = z$, and the desired result is immediate.

The “Substitution Lemma”

Lemma: If $\Gamma, x:S \vdash t : T$ and $\Gamma \vdash s : S$, then $\Gamma \vdash [x \mapsto s]t : T$.

Proof: By induction on the derivation of $\Gamma, x:S \vdash t : T$. Proceed by cases on the final typing rule used in the derivation.

Case T-ABS: $t = \lambda y:T_2. t_1$ $T = T_2 \rightarrow T_1$
 $\Gamma, x:S, y:T_2 \vdash t_1 : T_1$

By our conventions on choice of bound variable names, we may assume $x \neq y$ and $y \notin FV(s)$. Using *permutation* on the given subderivation, we obtain $\Gamma, y:T_2, x:S \vdash t_1 : T_1$. Using *weakening* on the other given derivation ($\Gamma \vdash s : S$), we obtain

$\Gamma, y:T_2 \vdash s : S$. Now, by the induction hypothesis,

$\Gamma, y:T_2 \vdash [x \mapsto s]t_1 : T_1$. By T-ABS,

$\Gamma \vdash \lambda y:T_2. [x \mapsto s]t_1 : T_2 \rightarrow T_1$, i.e. (by the definition of substitution), $\Gamma \vdash [x \mapsto s]\lambda y:T_2. t_1 : T_2 \rightarrow T_1$.

Summary: Preservation

Theorem: If $\Gamma \vdash t : T$ and $t \longrightarrow t'$, then $\Gamma \vdash t' : T$.

Lemmas to prove:

- ▶ Weakening
- ▶ Permutation
- ▶ Substitution preserves types
- ▶ Reduction preserves types (i.e., preservation)

Review: Type Systems

To define and verify a type system, you must:

1. Define types
2. Specify typing rules
3. Prove soundness: *progress* and *preservation*

Two Typing Topics

Erase

$$\text{erase}(x) = x$$

$$\text{erase}(\lambda x:T_1. t_2) = \lambda x. \text{erase}(t_2)$$

$$\text{erase}(t_1 \ t_2) = \text{erase}(t_1) \ \text{erase}(t_2)$$

Intro vs. elim forms

An *introduction form* for a given type gives us a way of *constructing* elements of this type.

An *elimination form* for a type gives us a way of *using* elements of this type.

The Curry-Howard Correspondence

In *constructive logics*, a proof of P must provide *evidence* for P .

- ▶ “law of the excluded middle” — $P \vee \neg P$ — not recognized.

A proof of $P \wedge Q$ is a *pair* of evidence for P and evidence for Q .

A proof of $P \supset Q$ is a *procedure* for transforming evidence for P into evidence for Q .

Propositions as Types

LOGIC

propositions

proposition $P \supset Q$

proposition $P \wedge Q$

proof of proposition P

proposition P is provable

PROGRAMMING LANGUAGES

types

type $P \rightarrow Q$

type $P \times Q$

term t of type P

type P is inhabited (by some term)
evaluation

Propositions as Types

LOGIC

propositions

proposition $P \supset Q$

proposition $P \wedge Q$

proof of proposition P

proposition P is provable

proof simplification

(a.k.a. “cut elimination”)

PROGRAMMING LANGUAGES

types

type $P \rightarrow Q$

type $P \times Q$

term t of type P

type P is inhabited (by some term)

evaluation

Extensions to STLC

Base types

Up to now, we've formulated “base types” (e.g. `Nat`) by adding them to the syntax of types, extending the syntax of terms with associated constants (`zero`) and operators (`succ`, etc.) and adding appropriate typing and evaluation rules. We can do this for as many base types as we like.

For more theoretical discussions (as opposed to programming) we can often ignore the term-level inhabitants of base types, and just treat these types as uninterpreted constants.

E.g., suppose `B` and `C` are some base types. Then we can ask (without knowing anything more about `B` or `C`) whether there are any types `S` and `T` such that the term

$$(\lambda f:S. \lambda g:T. f \ g) (\lambda x:B. x)$$

is well typed.

The Unit type

$t ::= \dots$
 unit

$v ::= \dots$
 unit

$T ::= \dots$
 Unit

terms
constant unit

values
constant unit

types
unit type

New typing rules

$\Gamma \vdash \text{unit} : \text{Unit}$

$\Gamma \vdash t : T$

(T-UNIT)

Sequencing

$t ::= \dots$
 $t_1; t_2$

terms

Sequencing

$t ::= \dots$
 $t_1; t_2$

terms

$$\frac{t_1 \longrightarrow t'_1}{t_1; t_2 \longrightarrow t'_1; t_2} \quad (\text{E-SEQ})$$

$$\text{unit}; t_2 \longrightarrow t_2 \quad (\text{E-SEQNEXT})$$

$$\frac{\Gamma \vdash t_1 : \text{Unit} \quad \Gamma \vdash t_2 : T_2}{\Gamma \vdash t_1; t_2 : T_2} \quad (\text{T-SEQ})$$

Derived forms

- ▶ Syntactic sugar
- ▶ Internal language vs. external (surface) language

Sequencing as a derived form

$$t_1; t_2 \stackrel{\text{def}}{=} (\lambda x:\text{Unit}. t_2) \ t_1$$

where $x \notin FV(t_2)$

Equivalence of the two definitions

[board]

Ascription

New syntactic forms

$t ::= \dots$
 $t \text{ as } T$

New evaluation rules

$v_1 \text{ as } T \longrightarrow v_1$

(E-ASCRIIBE)

$$\frac{t_1 \longrightarrow t'_1}{t_1 \text{ as } T \longrightarrow t'_1 \text{ as } T}$$

(E-ASCRIIBE1)

New typing rules

$\boxed{\Gamma \vdash t : T}$

$$\frac{\Gamma \vdash t_1 : T}{\Gamma \vdash t_1 \text{ as } T : T}$$

(T-ASCRIIBE)

terms

ascription

Ascription as a derived form

$$t \text{ as } T \stackrel{\text{def}}{=} (\lambda x:T. x) \ t$$

Let-bindings

New syntactic forms

$t ::= \dots$

$\text{let } x=t \text{ in } t$

New evaluation rules

terms

let binding

$t \longrightarrow t'$

$\text{let } x=v_1 \text{ in } t_2 \longrightarrow [x \mapsto v_1]t_2$ (E-LETV)

$$\frac{t_1 \longrightarrow t'_1}{\text{let } x=t_1 \text{ in } t_2 \longrightarrow \text{let } x=t'_1 \text{ in } t_2}$$
 (E-LET)

New typing rules

$\Gamma \vdash t : T$

$$\frac{\Gamma \vdash t_1 : T_1 \quad \Gamma, x:T_1 \vdash t_2 : T_2}{\Gamma \vdash \text{let } x=t_1 \text{ in } t_2 : T_2}$$
 (T-LET)

Pairs

$t ::= \dots$
 $\{t, t\}$
 $t.1$
 $t.2$

terms
pair
first projection
second projection

$v ::= \dots$
 $\{v, v\}$

values
pair value

$T ::= \dots$
 $T_1 \times T_2$

types
product type

Evaluation rules for pairs

$$\{v_1, v_2\}.1 \longrightarrow v_1 \quad (\text{E-PAIRBETA1})$$

$$\{v_1, v_2\}.2 \longrightarrow v_2 \quad (\text{E-PAIRBETA2})$$

$$\frac{t_1 \longrightarrow t'_1}{t_1.1 \longrightarrow t'_1.1} \quad (\text{E-PROJ1})$$

$$\frac{t_1 \longrightarrow t'_1}{t_1.2 \longrightarrow t'_1.2} \quad (\text{E-PROJ2})$$

$$\frac{t_1 \longrightarrow t'_1}{\{t_1, t_2\} \longrightarrow \{t'_1, t_2\}} \quad (\text{E-PAIR1})$$

$$\frac{t_2 \longrightarrow t'_2}{\{v_1, t_2\} \longrightarrow \{v_1, t'_2\}} \quad (\text{E-PAIR2})$$

Typing rules for pairs

$$\frac{\Gamma \vdash t_1 : T_1 \quad \Gamma \vdash t_2 : T_2}{\Gamma \vdash \{t_1, t_2\} : T_1 \times T_2} \quad (\text{T-PAIR})$$

$$\frac{\Gamma \vdash t_1 : T_{11} \times T_{12}}{\Gamma \vdash t_{1.1} : T_{11}} \quad (\text{T-PROJ1})$$

$$\frac{\Gamma \vdash t_1 : T_{11} \times T_{12}}{\Gamma \vdash t_{1.2} : T_{12}} \quad (\text{T-PROJ2})$$

Tuples

$t ::= \dots$
 $\{t_i \mid i \in 1..n\}$
 $t.i$

terms
tuple
projection

$v ::= \dots$
 $\{v_i \mid i \in 1..n\}$

values
tuple value

$T ::= \dots$
 $\{T_i \mid i \in 1..n\}$

types
tuple type

Evaluation rules for tuples

$$\{v_i \mid i \in 1..n\}.j \longrightarrow v_j \quad (\text{E-PROJTUPLE})$$

$$\frac{t_1 \longrightarrow t'_1}{t_1.i \longrightarrow t'_1.i} \quad (\text{E-PROJ})$$

$$\frac{t_j \longrightarrow t'_j}{\begin{array}{l} \{v_i \mid i \in 1..j-1, t_j, t_k \mid k \in j+1..n\} \\ \longrightarrow \{v_i \mid i \in 1..j-1, t'_j, t_k \mid k \in j+1..n\} \end{array}} \quad (\text{E-TUPLE})$$

Typing rules for tuples

$$\frac{\text{for each } i \quad \Gamma \vdash t_i : T_i}{\Gamma \vdash \{t_i\}_{i \in 1..n} : \{T_i\}_{i \in 1..n}} \quad (\text{T-TUPLE})$$

$$\frac{\Gamma \vdash t_1 : \{T_i\}_{i \in 1..n}}{\Gamma \vdash t_1.j : T_j} \quad (\text{T-PROJ})$$