SNU 4541.574
Programming Language Theory

Ack: from BCP's slides

Any Questions?

Plan

"We have the technology..."

- In this lecture and the next, we're going to cover some simple extensions of the typed-lambda calculus (TAPL Chapter 11).
  1. Products, records
  2. Sums, variants
  3. Recursion
- We're skipping Chapters 10 and 12.

Erasure and Typability

Erasure

We can transform terms in $\lambda_{\rightarrow}$ to terms of the untyped lambda-calculus simply by erasing type annotations on lambda-abstractions.

$$\begin{array}{lcl} \mathit{erase}(\mathtt{x}) & = & \mathtt{x} \\ \mathit{erase}(\lambda \mathtt{x}{:}\mathtt{T}_1.\ \mathtt{t}_2) & = & \lambda \mathtt{x}.\ \mathit{erase}(\mathtt{t}_2) \\ \mathit{erase}(\mathtt{t}_1\ \mathtt{t}_2) & = & \mathit{erase}(\mathtt{t}_1)\ \mathit{erase}(\mathtt{t}_2) \end{array}$$

Typability

Conversely, an untyped λ-term $\mathtt{m}$ is said to be *typable* if there is some term $\mathtt{t}$ in the simply typed lambda-calculus, some type $\mathtt{T}$, and some context Γ such that $\mathit{erase}(\mathtt{t}) = \mathtt{m}$ and $\Gamma \vdash \mathtt{t} : \mathtt{T}$.

This process is called *type reconstruction* or *type inference*.

Typability

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This process is called *type reconstruction* or *type inference*.

Example: Is the term

$$\lambda\mathtt{x.\ x\ x}$$

typable?

On to real programming languages...

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

```
(λf:S. λg:T. f g) (λx:B. x)
```

is well typed.

The `Unit` type

`t`	::=	...	*terms*
		`unit`	*constant* `unit`
`v`	::=	...	*values*
		`unit`	*constant* *`unit`*
`T`	::=	...	*types*
		`Unit`	*unit type*

New typing rules $\boxed{\Gamma \vdash \mathtt{t} : \mathtt{T}}$

$$\Gamma \vdash \mathtt{unit} : \mathtt{Unit} \qquad (\text{T-Unit})$$

Sequencing

$$\begin{array}{lll} \texttt{t} & ::= & \dots \\ & & \texttt{t}_1\texttt{;}\texttt{t}_2 \end{array} \qquad\qquad \textit{terms}$$

Sequencing

$$\texttt{t} ::= \ldots \qquad \textit{terms}$$
$$\qquad \texttt{t}_1\texttt{;t}_2$$

$$\frac{\texttt{t}_1 \longrightarrow \texttt{t}_1'}{\texttt{t}_1\texttt{;t}_2 \longrightarrow \texttt{t}_1'\texttt{;t}_2} \qquad \text{(E-Seq)}$$

$$\texttt{unit;t}_2 \longrightarrow \texttt{t}_2 \qquad \text{(E-SeqNext)}$$

$$\frac{\Gamma \vdash \texttt{t}_1 : \texttt{Unit} \qquad \Gamma \vdash \texttt{t}_2 : \texttt{T}_2}{\Gamma \vdash \texttt{t}_1\texttt{;t}_2 : \texttt{T}_2} \qquad \text{(T-Seq)}$$

Derived forms

- Syntatic sugar
- Internal language vs. external (surface) language

Sequencing as a derived form

$$\mathtt{t}_1\mathtt{;t}_2 \quad \stackrel{\text{def}}{=} \quad (\lambda\mathtt{x}\mathtt{:Unit.t}_2)\ \mathtt{t}_1$$
$$\text{where } \mathtt{x} \notin FV(\mathtt{t}_2)$$

Ascription

New syntactic forms

$$\begin{array}{llll} \mathtt{t} & ::= & \ldots & \textit{terms} \\ & & \mathtt{t}\ \mathtt{as}\ \mathtt{T} & \quad\textit{ascription} \end{array}$$

New evaluation rules $\boxed{\mathtt{t} \longrightarrow \mathtt{t}'}$

$$\mathtt{v}_1\ \mathtt{as}\ \mathtt{T} \longrightarrow \mathtt{v}_1 \qquad \text{(E-Ascribe)}$$

$$\frac{\mathtt{t}_1 \longrightarrow \mathtt{t}_1'}{\mathtt{t}_1\ \mathtt{as}\ \mathtt{T} \longrightarrow \mathtt{t}_1'\ \mathtt{as}\ \mathtt{T}} \qquad \text{(E-Ascribe1)}$$

New typing rules $\boxed{\Gamma \vdash \mathtt{t} : \mathtt{T}}$

$$\frac{\Gamma \vdash \mathtt{t}_1 : \mathtt{T}}{\Gamma \vdash \mathtt{t}_1\ \mathtt{as}\ \mathtt{T} : \mathtt{T}} \qquad \text{(T-Ascribe)}$$

Ascription as a derived form

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

Let-bindings

New syntactic forms

$\mathtt{t}$	$::=$	$\ldots$	*terms*
		$\mathtt{let\ x=t\ in\ t}$	*let binding*

New evaluation rules $\boxed{\mathtt{t} \longrightarrow \mathtt{t}'}$

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

$$\frac{\mathtt{t_1} \longrightarrow \mathtt{t_1'}}{\mathtt{let\ x=t_1\ in\ t_2} \longrightarrow \mathtt{let\ x=t_1'\ in\ t_2}} \qquad \text{(E-Let)}$$

New typing rules $\boxed{\Gamma \vdash \mathtt{t} : \mathtt{T}}$

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

Pairs, tuples, and records

Pairs

$\mathtt{t}$	::=	...	*terms*
		$\mathtt{\{t,t\}}$	*pair*
		$\mathtt{t.1}$	*first projection*
		$\mathtt{t.2}$	*second projection*
$\mathtt{v}$	::=	...	*values*
		$\mathtt{\{v,v\}}$	*pair value*
$\mathtt{T}$	::=	...	*types*
		$\mathtt{T}_1 \times \mathtt{T}_2$	*product type*

Evaluation rules for pairs

$$\{\mathtt{v}_1,\mathtt{v}_2\}.1 \longrightarrow \mathtt{v}_1 \qquad \text{(E-PairBeta1)}$$

$$\{\mathtt{v}_1,\mathtt{v}_2\}.2 \longrightarrow \mathtt{v}_2 \qquad \text{(E-PairBeta2)}$$

$$\frac{\mathtt{t}_1 \longrightarrow \mathtt{t}_1'}{\mathtt{t}_1.1 \longrightarrow \mathtt{t}_1'.1} \qquad \text{(E-Proj1)}$$

$$\frac{\mathtt{t}_1 \longrightarrow \mathtt{t}_1'}{\mathtt{t}_1.2 \longrightarrow \mathtt{t}_1'.2} \qquad \text{(E-Proj2)}$$

$$\frac{\mathtt{t}_1 \longrightarrow \mathtt{t}_1'}{\{\mathtt{t}_1,\mathtt{t}_2\} \longrightarrow \{\mathtt{t}_1',\mathtt{t}_2\}} \qquad \text{(E-Pair1)}$$

$$\frac{\mathtt{t}_2 \longrightarrow \mathtt{t}_2'}{\{\mathtt{v}_1,\mathtt{t}_2\} \longrightarrow \{\mathtt{v}_1,\mathtt{t}_2'\}} \qquad \text{(E-Pair2)}$$

Typing rules for pairs

$$\frac{\Gamma \vdash \mathtt{t}_1 : \mathtt{T}_1 \qquad \Gamma \vdash \mathtt{t}_2 : \mathtt{T}_2}{\Gamma \vdash \{\mathtt{t}_1,\mathtt{t}_2\} : \mathtt{T}_1 \times \mathtt{T}_2} \qquad \text{(T-Pair)}$$

$$\frac{\Gamma \vdash \mathtt{t}_1 : \mathtt{T}_{11} \times \mathtt{T}_{12}}{\Gamma \vdash \mathtt{t}_1\mathtt{.1} : \mathtt{T}_{11}} \qquad \text{(T-Proj1)}$$

$$\frac{\Gamma \vdash \mathtt{t}_1 : \mathtt{T}_{11} \times \mathtt{T}_{12}}{\Gamma \vdash \mathtt{t}_1\mathtt{.2} : \mathtt{T}_{12}} \qquad \text{(T-Proj2)}$$

Tuples

$\texttt{t}$	$::=$	$\ldots$	*terms*
		$\{\texttt{t}_i\ ^{i\in 1..n}\}$	*tuple*
		$\texttt{t.i}$	*projection*
$\texttt{v}$	$::=$	$\ldots$	*values*
		$\{\texttt{v}_i\ ^{i\in 1..n}\}$	*tuple value*
$\texttt{T}$	$::=$	$\ldots$	*types*
		$\{\texttt{T}_i\ ^{i\in 1..n}\}$	*tuple type*

Evaluation rules for tuples

$$\{\mathtt{v}_i\ ^{i\in 1..n}\}.\mathtt{j} \longrightarrow \mathtt{v}_j \qquad \text{(E-ProjTuple)}$$

$$\frac{\mathtt{t}_1 \longrightarrow \mathtt{t}_1'}{\mathtt{t}_1.\mathtt{i} \longrightarrow \mathtt{t}_1'.\mathtt{i}} \qquad \text{(E-Proj)}$$

$$\frac{\mathtt{t}_j \longrightarrow \mathtt{t}_j'}{\begin{array}{c}\{\mathtt{v}_i\ ^{i\in 1..j-1},\mathtt{t}_j,\mathtt{t}_k\ ^{k\in j+1..n}\}\\ \longrightarrow \{\mathtt{v}_i\ ^{i\in 1..j-1},\mathtt{t}_j',\mathtt{t}_k\ ^{k\in j+1..n}\}\end{array}} \qquad \text{(E-Tuple)}$$

Typing rules for tuples

$$\frac{\text{for each } i \quad \Gamma \vdash \mathtt{t}_i : \mathtt{T}_i}{\Gamma \vdash \{\mathtt{t}_i{}^{\,i \in 1..n}\} : \{\mathtt{T}_i{}^{\,i \in 1..n}\}} \qquad \text{(T-Tuple)}$$

$$\frac{\Gamma \vdash \mathtt{t}_1 : \{\mathtt{T}_i{}^{\,i \in 1..n}\}}{\Gamma \vdash \mathtt{t}_1\mathtt{.j} : \mathtt{T}_j} \qquad \text{(T-Proj)}$$

Records

$\mathtt{t}$	$::=$	$\ldots$	*terms*
		$\{\mathtt{l}_i\mathtt{=}\mathtt{t}_i\ ^{i\in 1..n}\}$	*record*
		$\mathtt{t.l}$	*projection*
$\mathtt{v}$	$::=$	$\ldots$	*values*
		$\{\mathtt{l}_i\mathtt{=}\mathtt{v}_i\ ^{i\in 1..n}\}$	*record value*
$\mathtt{T}$	$::=$	$\ldots$	*types*
		$\{\mathtt{l}_i\mathtt{:}\mathtt{T}_i\ ^{i\in 1..n}\}$	*type of records*

Evaluation rules for records

$$\{\mathtt{l}_i\mathtt{=}\mathtt{v}_i{}^{\,i\in 1..n}\}\mathtt{.l}_j \longrightarrow \mathtt{v}_j \qquad \text{(E-ProjRcd)}$$

$$\frac{\mathtt{t}_1 \longrightarrow \mathtt{t}_1'}{\mathtt{t}_1\mathtt{.l} \longrightarrow \mathtt{t}_1'\mathtt{.l}} \qquad \text{(E-Proj)}$$

$$\frac{\mathtt{t}_j \longrightarrow \mathtt{t}_j'}{\begin{array}{c}\{\mathtt{l}_i\mathtt{=}\mathtt{v}_i{}^{\,i\in 1..j-1}\mathtt{,}\mathtt{l}_j\mathtt{=}\mathtt{t}_j\mathtt{,}\mathtt{l}_k\mathtt{=}\mathtt{t}_k{}^{\,k\in j+1..n}\} \\ \longrightarrow \{\mathtt{l}_i\mathtt{=}\mathtt{v}_i{}^{\,i\in 1..j-1}\mathtt{,}\mathtt{l}_j\mathtt{=}\mathtt{t}_j'\mathtt{,}\mathtt{l}_k\mathtt{=}\mathtt{t}_k{}^{\,k\in j+1..n}\}\end{array}} \qquad \text{(E-Rcd)}$$

Typing rules for records

$$\frac{\text{for each } i \quad \Gamma \vdash \mathtt{t}_i : \mathtt{T}_i}{\Gamma \vdash \{\mathtt{l}_i\mathtt{=}\mathtt{t}_i \ ^{i\in 1..n}\} : \{\mathtt{l}_i\mathtt{:}\mathtt{T}_i \ ^{i\in 1..n}\}} \qquad \text{(T-Rcd)}$$

$$\frac{\Gamma \vdash \mathtt{t}_1 : \{\mathtt{l}_i\mathtt{:}\mathtt{T}_i \ ^{i\in 1..n}\}}{\Gamma \vdash \mathtt{t}_1\mathtt{.l}_j : \mathtt{T}_j} \qquad \text{(T-Proj)}$$

Sums and variants

Sums – motivating example

```
PhysicalAddr = {firstlast:String, addr:String}
VirtualAddr  = {name:String, email:String}
Addr         = PhysicalAddr + VirtualAddr
inl  :  “PhysicalAddr → PhysicalAddr+VirtualAddr”
inr  :  “VirtualAddr → PhysicalAddr+VirtualAddr”
```

```
getName = λa:Addr.
  case a of
    inl x ⇒ x.firstlast
  | inr y ⇒ y.name;
```

New syntactic forms

`t`	::=	...	*terms*
		`inl t`	*tagging (left)*
		`inr t`	*tagging (right)*
		`case t of inl x⇒t | inr x⇒t`	*case*
`v`	::=	...	*values*
		`inl v`	*tagged value (left)*
		`inr v`	*tagged value (right)*
`T`	::=	...	*types*
		`T+T`	*sum type*

T_1+T_2 is a *disjoint union* of T_1 and T_2 (the tags `inl` and `inr` ensure disjointness)

New evaluation rules $\boxed{\mathtt{t} \longrightarrow \mathtt{t}'}$

$$\begin{array}{l} \mathtt{case\ (inl\ v_0)} \\ \mathtt{of\ inl\ x_1{\Rightarrow}t_1\ |\ inr\ x_2{\Rightarrow}t_2} \end{array} \longrightarrow [\mathtt{x_1} \mapsto \mathtt{v_0}]\mathtt{t_1} \quad \text{(E-CaseInl)}$$

$$\begin{array}{l} \mathtt{case\ (inr\ v_0)} \\ \mathtt{of\ inl\ x_1{\Rightarrow}t_1\ |\ inr\ x_2{\Rightarrow}t_2} \end{array} \longrightarrow [\mathtt{x_2} \mapsto \mathtt{v_0}]\mathtt{t_2} \quad \text{(E-CaseInr)}$$

$$\frac{\mathtt{t_0} \longrightarrow \mathtt{t_0'}}{\begin{array}{l} \mathtt{case\ t_0\ of\ inl\ x_1{\Rightarrow}t_1\ |\ inr\ x_2{\Rightarrow}t_2} \\ \longrightarrow \mathtt{case\ t_0'\ of\ inl\ x_1{\Rightarrow}t_1\ |\ inr\ x_2{\Rightarrow}t_2} \end{array}} \quad \text{(E-Case)}$$

$$\frac{\mathtt{t_1} \longrightarrow \mathtt{t_1'}}{\mathtt{inl\ t_1} \longrightarrow \mathtt{inl\ t_1'}} \quad \text{(E-Inl)}$$

$$\frac{\mathtt{t_1} \longrightarrow \mathtt{t_1'}}{\mathtt{inr\ t_1} \longrightarrow \mathtt{inr\ t_1'}} \quad \text{(E-Inr)}$$

New typing rules

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

$$\frac{\Gamma \vdash \mathtt{t}_1 : \mathtt{T}_1}{\Gamma \vdash \mathtt{inl}\ \mathtt{t}_1 : \mathtt{T}_1\mathtt{+}\mathtt{T}_2} \quad \text{(T-Inl)}$$

$$\frac{\Gamma \vdash \mathtt{t}_1 : \mathtt{T}_2}{\Gamma \vdash \mathtt{inr}\ \mathtt{t}_1 : \mathtt{T}_1\mathtt{+}\mathtt{T}_2} \quad \text{(T-Inr)}$$

$$\frac{\begin{array}{c}\Gamma \vdash \mathtt{t}_0 : \mathtt{T}_1\mathtt{+}\mathtt{T}_2 \\ \Gamma, \mathtt{x}_1\mathtt{:}\mathtt{T}_1 \vdash \mathtt{t}_1 : \mathtt{T} \qquad \Gamma, \mathtt{x}_2\mathtt{:}\mathtt{T}_2 \vdash \mathtt{t}_2 : \mathtt{T}\end{array}}{\Gamma \vdash \mathtt{case}\ \mathtt{t}_0\ \mathtt{of}\ \mathtt{inl}\ \mathtt{x}_1 \Rightarrow \mathtt{t}_1\ \mathtt{|}\ \mathtt{inr}\ \mathtt{x}_2 \Rightarrow \mathtt{t}_2 : \mathtt{T}} \quad \text{(T-Case)}$$

Sums and Uniqueness of Types

Problem:

> *If* `t` *has type* `T`*, then* `inl t` *has type* `T+U` *for every* `U`*.*

I.e., we've lost uniqueness of types.

Possible solutions:

- "Infer" `U` as needed during typechecking
- Give constructors different names and only allow each name to appear in one sum type (requires generalization to "variants," which we'll see next) — OCaml's solution
- Annotate each `inl` and `inr` with the intended sum type.

For simplicity, let's choose the third.

New syntactic forms

`t`	::=	...	*terms*
		`inl t as T`	*tagging (left)*
		`inr t as T`	*tagging (right)*
`v`	::=	...	*values*
		`inl v as T`	*tagged value (left)*
		`inr v as T`	*tagged value (right)*

Note that `as T` here is not the ascription operator that we saw before — i.e., not a separate syntactic form: in essence, there is an ascription “built into” every use of `inl` or `inr`.

New typing rules

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

$$\frac{\Gamma \vdash \mathtt{t}_1 : \mathtt{T}_1}{\Gamma \vdash \mathtt{inl}\ \mathtt{t}_1\ \mathtt{as}\ \mathtt{T}_1\mathtt{+}\mathtt{T}_2 : \mathtt{T}_1\mathtt{+}\mathtt{T}_2} \qquad \text{(T-Inl)}$$

$$\frac{\Gamma \vdash \mathtt{t}_1 : \mathtt{T}_2}{\Gamma \vdash \mathtt{inr}\ \mathtt{t}_1\ \mathtt{as}\ \mathtt{T}_1\mathtt{+}\mathtt{T}_2 : \mathtt{T}_1\mathtt{+}\mathtt{T}_2} \qquad \text{(T-Inr)}$$

Evaluation rules ignore annotations:

$\boxed{\mathtt{t} \longrightarrow \mathtt{t}'}$

$$\begin{array}{l}\mathtt{case}\ (\mathtt{inl}\ \mathtt{v}_0\ \mathtt{as}\ \mathtt{T}_0)\\ \mathtt{of}\ \mathtt{inl}\ \mathtt{x}_1 \Rightarrow \mathtt{t}_1 \mid \mathtt{inr}\ \mathtt{x}_2 \Rightarrow \mathtt{t}_2\\ \qquad \longrightarrow [\mathtt{x}_1 \mapsto \mathtt{v}_0]\mathtt{t}_1\end{array} \qquad \text{(E-CaseInl)}$$

$$\begin{array}{l}\mathtt{case}\ (\mathtt{inr}\ \mathtt{v}_0\ \mathtt{as}\ \mathtt{T}_0)\\ \mathtt{of}\ \mathtt{inl}\ \mathtt{x}_1 \Rightarrow \mathtt{t}_1 \mid \mathtt{inr}\ \mathtt{x}_2 \Rightarrow \mathtt{t}_2\\ \qquad \longrightarrow [\mathtt{x}_2 \mapsto \mathtt{v}_0]\mathtt{t}_2\end{array} \qquad \text{(E-CaseInr)}$$

$$\frac{\mathtt{t}_1 \longrightarrow \mathtt{t}_1'}{\mathtt{inl}\ \mathtt{t}_1\ \mathtt{as}\ \mathtt{T}_2 \longrightarrow \mathtt{inl}\ \mathtt{t}_1'\ \mathtt{as}\ \mathtt{T}_2} \qquad \text{(E-Inl)}$$

$$\frac{\mathtt{t}_1 \longrightarrow \mathtt{t}_1'}{\mathtt{inr}\ \mathtt{t}_1\ \mathtt{as}\ \mathtt{T}_2 \longrightarrow \mathtt{inr}\ \mathtt{t}_1'\ \mathtt{as}\ \mathtt{T}_2} \qquad \text{(E-Inr)}$$

Variants

Just as we generalized binary products to labeled records, we can generalize binary sums to labeled *variants*.

New syntactic forms

$\mathtt{t}$	$::=$	...	*terms*
		$\mathtt{<l=t>\ as\ T}$	*tagging*
		$\mathtt{case\ t\ of\ <l_i=x_i>}\Rightarrow\mathtt{t_i}\ ^{i\in 1..n}$	*case*
$\mathtt{T}$	$::=$	...	*types*
		$\mathtt{<l_i:T_i}\ ^{i\in 1..n}\mathtt{>}$	*type of variants*

New evaluation rules

$$\boxed{\mathtt{t} \longrightarrow \mathtt{t}'}$$

$$\begin{array}{l}\mathtt{case}\ (\mathtt{<l}_j\mathtt{=v}_j\mathtt{>}\ \mathtt{as}\ \mathtt{T})\ \mathtt{of}\ \mathtt{<l}_i\mathtt{=x}_i\mathtt{>}\Rightarrow\mathtt{t}_i\ {}^{i\in 1..n} \\ \qquad\qquad \longrightarrow [\mathtt{x}_j \mapsto \mathtt{v}_j]\mathtt{t}_j\end{array} \qquad \text{(E-CaseVariant)}$$

$$\frac{\mathtt{t}_0 \longrightarrow \mathtt{t}_0'}{\begin{array}{l}\mathtt{case}\ \mathtt{t}_0\ \mathtt{of}\ \mathtt{<l}_i\mathtt{=x}_i\mathtt{>}\Rightarrow\mathtt{t}_i\ {}^{i\in 1..n} \\ \longrightarrow \mathtt{case}\ \mathtt{t}_0'\ \mathtt{of}\ \mathtt{<l}_i\mathtt{=x}_i\mathtt{>}\Rightarrow\mathtt{t}_i\ {}^{i\in 1..n}\end{array}} \qquad \text{(E-Case)}$$

$$\frac{\mathtt{t}_i \longrightarrow \mathtt{t}_i'}{\mathtt{<l}_i\mathtt{=t}_i\mathtt{>}\ \mathtt{as}\ \mathtt{T} \longrightarrow \mathtt{<l}_i\mathtt{=t}_i'\mathtt{>}\ \mathtt{as}\ \mathtt{T}} \qquad \text{(E-Variant)}$$

New typing rules

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

$$\frac{\Gamma \vdash \mathtt{t}_j : \mathtt{T}_j}{\Gamma \vdash \mathtt{<l}_j\mathtt{=t}_j\mathtt{>}\ \mathtt{as}\ \mathtt{<l}_i\mathtt{:T}_i\ {}^{i\in 1..n}\mathtt{>} : \mathtt{<l}_i\mathtt{:T}_i\ {}^{i\in 1..n}\mathtt{>}} \quad (\text{T-Variant})$$

$$\frac{\begin{array}{c}\Gamma \vdash \mathtt{t}_0 : \mathtt{<l}_i\mathtt{:T}_i\ {}^{i\in 1..n}\mathtt{>} \\ \text{for each } i \quad \Gamma, \mathtt{x}_i\mathtt{:T}_i \vdash \mathtt{t}_i : \mathtt{T}\end{array}}{\Gamma \vdash \mathtt{case}\ \mathtt{t}_0\ \mathtt{of}\ \mathtt{<l}_i\mathtt{=x}_i\mathtt{>}\Rightarrow\mathtt{t}_i\ {}^{i\in 1..n} : \mathtt{T}} \quad (\text{T-Case})$$

Example

```
Addr = <physical:PhysicalAddr, virtual:VirtualAddr>;

a = <physical=pa> as Addr;

getName = λa:Addr.
  case a of
    <physical=x> ⇒ x.firstlast
  | <virtual=y> ⇒ y.name;
```

Options

Just like in OCaml...

```
OptionalNat = <none:Unit, some:Nat>;

Table = Nat→OptionalNat;

emptyTable = λn:Nat. <none=unit> as OptionalNat;

extendTable =
  λt:Table. λm:Nat. λv:Nat.
    λn:Nat.
      if equal n m then <some=v> as OptionalNat
      else t n;

x = case t(5) of
      <none=u> ⇒ 999
    | <some=v> ⇒ v;
```

Enumerations

```
Weekday = <monday:Unit, tuesday:Unit, wednesday:Unit,
           thursday:Unit, friday:Unit>;

nextBusinessDay = λw:Weekday.
  case w of <monday=x>    ⇒ <tuesday=unit> as Weekday
          | <tuesday=x>   ⇒ <wednesday=unit> as Weekday
          | <wednesday=x> ⇒ <thursday=unit> as Weekday
          | <thursday=x>  ⇒ <friday=unit> as Weekday
          | <friday=x>    ⇒ <monday=unit> as Weekday;
```

Recursion

Recursion in $\lambda_{\rightarrow}$

- In $\lambda_{\rightarrow}$, all programs terminate. (Cf. Chapter 12.)
- Hence, untyped terms like `omega` and `fix` are not typable.
- But we can *extend* the system with a (typed) fixed-point operator...

Example

```
ff = λie:Nat→Bool.
       λx:Nat.
         if iszero x then true
         else if iszero (pred x) then false
         else ie (pred (pred x));

iseven = fix ff;

iseven 7;
```

New syntactic forms

$$\begin{array}{llll} \mathtt{t} & ::= & \ldots & \textit{terms} \\ & & \mathtt{fix\ t} & \textit{fixed point of } \mathtt{t} \end{array}$$

New evaluation rules $\boxed{\mathtt{t} \longrightarrow \mathtt{t'}}$

$$\begin{array}{c} \mathtt{fix\ (\lambda x\!:\!T_1.t_2)} \\ \longrightarrow [\mathtt{x} \mapsto \mathtt{(fix\ (\lambda x\!:\!T_1.t_2))}]\mathtt{t_2} \end{array} \qquad \text{(E-FixBeta)}$$

$$\frac{\mathtt{t_1} \longrightarrow \mathtt{t_1'}}{\mathtt{fix\ t_1} \longrightarrow \mathtt{fix\ t_1'}} \qquad \text{(E-Fix)}$$

New typing rules

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

$$\frac{\Gamma \vdash \mathtt{t}_1 : \mathtt{T}_1 \to \mathtt{T}_1}{\Gamma \vdash \mathtt{fix}\ \mathtt{t}_1 : \mathtt{T}_1} \qquad \text{(T-Fix)}$$

A more convenient form

$$\texttt{letrec x:T}_1\texttt{=t}_1\texttt{ in t}_2 \quad \stackrel{\text{def}}{=} \quad \texttt{let x = fix (}\lambda\texttt{x:T}_1\texttt{.t}_1\texttt{) in t}_2$$

```
letrec iseven : Nat→Bool =
  λx:Nat.
    if iszero x then true
    else if iszero (pred x) then false
    else iseven (pred (pred x))
in
  iseven 7;
```