

# Foundations of Software Fall 2023

Week 7

# Plan

PREVIOUSLY: unit, sequencing, let, pairs, tuples

TODAY:

1. options, variants
2. recursion
3. state

NEXT: exceptions?

NEXT: polymorphic (not so simple) typing

# Records

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

*terms*  
*record*  
*projection*

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

*values*  
*record value*

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

*types*  
*type of records*

## Evaluation rules for records

$$\{l_i = v_i \mid i \in 1..n\} . l_j \longrightarrow v_j \quad (\text{E-PROJRCd})$$

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

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

## Typing rules for records

$$\frac{\text{for each } i \quad \Gamma \vdash t_i : T_i}{\Gamma \vdash \{l_i = t_i \mid i \in 1..n\} : \{l_i : T_i \mid i \in 1..n\}} \quad (\text{T-RCD})$$

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

# 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 =  $\lambda$ a:Addr.
  case a of
    inl x  $\Rightarrow$  x.firstlast
  | inr y  $\Rightarrow$  y.name;
```

## New syntactic forms

$t ::=$	...	terms
	<code>inl t</code>	<i>tagging (left)</i>
	<code>inr t</code>	<i>tagging (right)</i>
	<code>case t of inl <math>x \Rightarrow t</math>   inr <math>x \Rightarrow t</math></code>	<i>case</i>
$v ::=$	...	values
	<code>inl v</code>	<i>tagged value (left)</i>
	<code>inr v</code>	<i>tagged value (right)</i>
$T ::=$	...	types
	<code>T+T</code>	<i>sum type</i>

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



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

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

$$\frac{t_0 \longrightarrow t'_0}{\begin{array}{l} \text{case } t_0 \text{ of inl } x_1 \Rightarrow t_1 \mid \text{inr } x_2 \Rightarrow t_2 \\ \longrightarrow \text{case } t'_0 \text{ of inl } x_1 \Rightarrow t_1 \mid \text{inr } x_2 \Rightarrow t_2 \end{array}} \quad (\text{E-CASE})$$

$$\frac{t_1 \longrightarrow t'_1}{\text{inl } t_1 \longrightarrow \text{inl } t'_1} \quad (\text{E-INL})$$

$$\frac{t_1 \longrightarrow t'_1}{\text{inr } t_1 \longrightarrow \text{inr } t'_1} \quad (\text{E-INR})$$

$$\frac{\Gamma \vdash t_1 : T_1}{\Gamma \vdash \text{inl } t_1 : T_1 + T_2} \quad (\text{T-INL})$$

$$\frac{\Gamma \vdash t_1 : T_2}{\Gamma \vdash \text{inr } t_1 : T_1 + T_2} \quad (\text{T-INR})$$

$$\frac{\begin{array}{c} \Gamma \vdash t_0 : T_1 + T_2 \\ \Gamma, x_1 : T_1 \vdash t_1 : T \quad \Gamma, x_2 : T_2 \vdash t_2 : T \end{array}}{\Gamma \vdash \text{case } t_0 \text{ of inl } x_1 \Rightarrow t_1 \mid \text{inr } x_2 \Rightarrow t_2 : T} \quad (\text{T-CASE})$$

# Types of Sums

Consider the term

$t = \text{inl } (\text{succ } 0)$

**Clicker question:** What can we say about it? (multiple possible answers)

- A.  $\vdash t : \text{Nat}$
- B.  $\vdash t : \text{Nat} + \text{Bool}$
- C.  $\vdash t : \text{Bool} + \text{Nat}$
- D.  $\vdash t : \text{Nat} + \text{Nat}$

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# Sums and Uniqueness of Types

Problem:

*If  $t$  has type  $T$ , then  $\text{inl } t$  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  $\text{inl}$  and  $\text{inr}$  with the intended sum type
- ▶ (Add subtyping and a “bottom” ( $\text{Nothing}$ ) type — Scala's solution)

For simplicity, let's choose the third.

## *New syntactic forms*

`t ::= ...`  
    `inl t as T`  
    `inr t as T`

*terms*  
    *tagging (left)*  
    *tagging (right)*

`v ::= ...`  
    `inl v as T`  
    `inr v as T`

*values*  
    *tagged value (left)*  
    *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*

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

$$\frac{\Gamma \vdash t_1 : T_1}{\Gamma \vdash \text{inl } t_1 \text{ as } T_1+T_2 : T_1+T_2} \quad (\text{T-INL})$$

$$\frac{\Gamma \vdash t_1 : T_2}{\Gamma \vdash \text{inr } t_1 \text{ as } T_1+T_2 : T_1+T_2} \quad (\text{T-INR})$$

*Evaluation rules ignore annotations:*

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

$$\begin{array}{l} \text{case (inl } v_0 \text{ as } T_0) \\ \text{of inl } x_1 \Rightarrow t_1 \mid \text{inr } x_2 \Rightarrow t_2 \\ \longrightarrow [x_1 \mapsto v_0]t_1 \end{array} \quad (\text{E-CASEINL})$$

$$\begin{array}{l} \text{case (inr } v_0 \text{ as } T_0) \\ \text{of inl } x_1 \Rightarrow t_1 \mid \text{inr } x_2 \Rightarrow t_2 \\ \longrightarrow [x_2 \mapsto v_0]t_2 \end{array} \quad (\text{E-CASEINR})$$

$$\frac{t_1 \longrightarrow t'_1}{\text{inl } t_1 \text{ as } T_2 \longrightarrow \text{inl } t'_1 \text{ as } T_2} \quad (\text{E-INL})$$

$$\frac{t_1 \longrightarrow t'_1}{\text{inr } t_1 \text{ as } T_2 \longrightarrow \text{inr } t'_1 \text{ as } T_2} \quad (\text{E-INR})$$

## Variants

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



## *New syntactic forms*

$t ::= \dots$   
     $\langle l=t \rangle \text{ as } T$   
    case  $t$  of  $\langle l_i=x_i \rangle \Rightarrow t_i \quad i \in 1..n$

*terms*  
    *tagging*  
    *case*

$T ::= \dots$   
     $\langle l_i:T_i \quad i \in 1..n \rangle$

*types*  
    *type of variants*

$$\text{case } (\langle l_j = v_j \rangle \text{ as } T) \text{ of } \langle l_i = x_i \rangle \Rightarrow t_i \text{ }^{i \in 1..n} \quad (\text{E-CASEVARIANT}) \\ \longrightarrow [x_j \mapsto v_j] t_j$$

$$\frac{t_0 \longrightarrow t'_0}{\text{case } t_0 \text{ of } \langle l_i = x_i \rangle \Rightarrow t_i \text{ }^{i \in 1..n} \longrightarrow \text{case } t'_0 \text{ of } \langle l_i = x_i \rangle \Rightarrow t_i \text{ }^{i \in 1..n}} \quad (\text{E-CASE})$$

$$\frac{t_i \longrightarrow t'_i}{\langle l_i = t_i \rangle \text{ as } T \longrightarrow \langle l_i = t'_i \rangle \text{ as } T} \quad (\text{E-VARIANT})$$

$$\frac{\Gamma \vdash t_j : T_j}{\Gamma \vdash \langle l_j = t_j \rangle \text{ as } \langle l_i : T_i \rangle_{i \in 1..n} : \langle l_i : T_i \rangle_{i \in 1..n}} \text{ (T-VARIANT)}$$

$$\frac{\begin{array}{c} \Gamma \vdash t_0 : \langle l_i : T_i \rangle_{i \in 1..n} \\ \text{for each } i \quad \Gamma, x_i : T_i \vdash t_i : T \end{array}}{\Gamma \vdash \text{case } t_0 \text{ of } \langle l_i = x_i \rangle \Rightarrow t_i \rangle_{i \in 1..n} : T} \text{ (T-CASE)}$$

## Example

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

```
a = <physical=pa> as Addr;
```

```
getName =  $\lambda$ a:Addr.
```

```
  case a of
```

```
    <physical=x>  $\Rightarrow$  x.firstlast
```

```
  | <virtual=y>  $\Rightarrow$  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;
```