

Lecture 18 – Type Systems

COSE212: Programming Languages

Jihyeok Park



2023 Fall

- We learned about **continuations** with the following topics:
 - **Continuations** (Lecture 14 & 15)
 - **First-Class Continuations** (Lecture 16)
 - **Compiling with continuations** (Lecture 17)
- From now on, we will learn about **type systems** with the following topics until the end of the semester:
 - Typed Languages
 - Typing Recursive Functions
 - Algebraic Data Types
 - Parametric Polymorphism
 - Subtype Polymorphism
 - Type Inference
- In this lecture, we will focus on the **motivation** and **basic concepts** of type systems.

1. Motivation: Safe Language Systems

- Detecting Run-Time Errors

- Dynamic vs Static Analysis

- Soundness vs Completeness

2. Type Systems

- Types

- Type Errors

- Type Checking

- Type Soundness

1. Motivation: Safe Language Systems

- Detecting Run-Time Errors

- Dynamic vs Static Analysis

- Soundness vs Completeness

2. Type Systems

- Types

- Type Errors

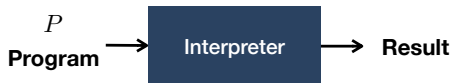
- Type Checking

- Type Soundness

So far, we have designed diverse programming languages with:

- **Syntax**: a grammar that defines the structure of programs
- **Semantics**: a set of rules that defines the meaning of programs

and implemented their **interpreters** in Scala:



However, we don't have any automatic system to **check** whether a program is evaluated without any **run-time errors**.

For example, following FAE expressions are syntactically correct, but they throw **run-time errors**:

```
/* FAE */  
x * 42           // error: free identifier  
0 + (x => x)      // error: cannot add a function  
1(2)            // error: cannot apply a number
```

Unexpected errors in **safety-critical software** cause serious problems:

<p>June 4, 1996: Ariane-5 explodes after lift off</p> <p>Today in History: June 4, 1996: Ariane-5 explodes after lift off</p> <p>Published November 6, 2023 at 2:00 p.m. EST · Published November 6, 2023 at 2:00 p.m. EST</p> 	<p>Knight Capital Says Trading Glitch Cost It</p> <p>BY NATHANIEL POPPER AUGUST 3, 2013 9:07 AM</p> <p>Runaway Trades Spread Turmoil Across Wall St.</p> 	<p>Heathrow Airport apologises for IT failure disruption</p> <p>By 14 February 2020</p> 	<p>Cruise recalls all its driverless cars</p> <p>pedestrian hit and dragged</p> <p>In another setback, Cruise updates software on 950 driverless cars to fix its 'Collision Detection'</p> <p>By David X. Charles</p> <p>Published November 6, 2023 at 2:00 p.m. EST · Published November 6, 2023 at 2:00 p.m. EST</p> 
Rocket	Financial	Airport	Auto. Vehicle
(1996)	(2012)	(2020)	(2023)

Then, how can we **prevent** such errors?

Can we **automatically** check whether a program does not have any **run-time errors**?

We can use various **analysis** techniques to detect run-time errors:



An **analyzer** is a program that takes a program as an input and determines whether the program has a certain property. In this case, the property is **run-time errors**.

We can categorize them into two groups:

- **Dynamic Analysis**: analyze programs by **executing** them
- **Static Analysis**: analyze programs **without executing** them

Dynamic analysis is a program analysis technique by **executing** them.

Let's perform **dynamic analysis** for the following Scala program:

```
def abs(x: Int): Int = { /* L1 */  
  if (x < 0)             /* L2 */  
    -x                   /* L3 */  
  else                   /* L4 */  
    x                    /* L5 */  
}                         /* L6 */
```


Dynamic analysis is a program analysis technique by **executing** them.

Let's perform **dynamic analysis** for the following Scala program:

```
def abs(x: Int): Int = { /* L1 */  
  if (x < 0)             /* L2 */  
    -x                   /* L3 */  
  else                   /* L4 */  
    x                    /* L5 */  
}                         /* L6 */
```

L1	-5
L2	-5
L3	5
L4	
L5	
L6	5

Dynamic analysis is a program analysis technique by **executing** them.

Let's perform **dynamic analysis** for the following Scala program:

```
def abs(x: Int): Int = { /* L1 */  
  if (x < 0)             /* L2 */  
    -x                   /* L3 */  
  else                   /* L4 */  
    x                    /* L5 */  
}                         /* L6 */
```

L1	-5	42
L2	-5	
L3	5	
L4		42
L5		42
L6	5	42

Dynamic analysis is a program analysis technique by **executing** them.

Let's perform **dynamic analysis** for the following Scala program:

```
def abs(x: Int): Int = { /* L1 */  
  if (x < 0)             /* L2 */  
    -x                   /* L3 */  
  else                   /* L4 */  
    x                    /* L5 */  
}                         /* L6 */
```

L1	-5	42	-7	99	0	...
L2	-5		-7			...
L3	5		7			...
L4		42		99	0	...
L5		42		99	0	...
L6	5	42	7	99	0	...

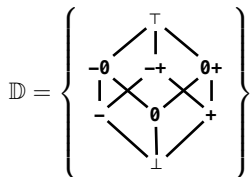
We can easily get the **behavior** of the program for each **single input**.

However, it is **difficult** to get all the **possible behaviors** of the program for **all the inputs**.

Static analysis is a program analysis technique **without executing** them.

Let's perform **static analysis** for the following Scala program:

```
def abs(x: Int): Int = { /* L1 */
  if (x < 0)             /* L2 */
    -x                  /* L3 */
  else                  /* L4 */
    x                   /* L5 */
}                       /* L6 */
```



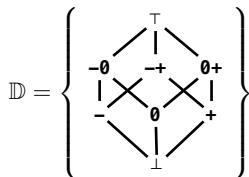
Let's define an **abstract domain** \mathbb{D} for integers to analyze the program.

$$\begin{array}{lll} \perp & = \emptyset & \top = \mathbb{Z} \\ 0 & = \{0\} & - = \{x \in \mathbb{Z} \mid x < 0\} \quad + = \{x \in \mathbb{Z} \mid x > 0\} \\ -0 & = - \cup 0 & -+ = - \cup + \quad 0+ = 0 \cup + \end{array}$$

Static analysis is a program analysis technique **without executing** them.

Let's perform **static analysis** for the following Scala program:

```
def abs(x: Int): Int = { /* L1 */
  if (x < 0)             /* L2 */
    -x                   /* L3 */
  else                   /* L4 */
    x                     /* L5 */
}                          /* L6 */
```



L1	
L2	
L3	
L4	
L5	
L6	

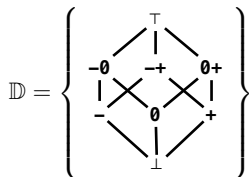
Let's define an **abstract domain** \mathbb{D} for integers to analyze the program:

$$\begin{array}{lll} \perp & = \emptyset & \top = \mathbb{Z} \\ 0 & = \{0\} & - = \{x \in \mathbb{Z} \mid x < 0\} \quad + = \{x \in \mathbb{Z} \mid x > 0\} \\ -0 & = - \cup 0 & -+ = - \cup + \quad 0+ = 0 \cup + \end{array}$$

Static analysis is a program analysis technique **without executing** them.

Let's perform **static analysis** for the following Scala program:

```
def abs(x: Int): Int = { /* L1 */
  if (x < 0)             /* L2 */
    -x                  /* L3 */
  else                  /* L4 */
    x                   /* L5 */
}                       /* L6 */
```



L1	\top
L2	$-$
L3	$+$
L4	$0+$
L5	$0+$
L6	$0+$

Let's define an **abstract domain** \mathbb{D} for integers to analyze the program:

$$\begin{array}{lll} \perp & = \emptyset & \top = \mathbb{Z} \\ 0 & = \{0\} & - = \{x \in \mathbb{Z} \mid x < 0\} \quad + = \{x \in \mathbb{Z} \mid x > 0\} \\ -0 & = - \cup 0 & -+ = - \cup + \quad 0+ = 0 \cup + \end{array}$$

We can prove that `abs` always returns a **non-negative** integer (i.e., $0+$).

- $\models \psi$ denotes that a statement ψ is **provable**.
- $\vdash \psi$ denotes that a statement ψ is **true**.

In a **sound** proof system, all **provable** statements are **true**.

$$\models \psi \quad \Longrightarrow \quad \vdash \psi$$

In a **complete** proof system, all **true** statements are **provable**.

$$\vdash \psi \quad \Longrightarrow \quad \models \psi$$

Analysis techniques can be used to prove that a program is **error-free**.

- $\models P$ denotes that a program P is **analyzed** as error-free.
- $\vdash P$ denotes that a program P is truly **error-free**.

Then, is dynamic/static analysis **sound** or **complete**?

- **Dynamic analysis** is **complete** but **unsound** in general.
 - All the detected errors are **true alarms** (**true positive (TP)**).
 - It will not detect any errors in error-free programs.
 - It suffers from **missing errors** (**false negative (FN)**).
- **Static analysis** is **sound** but **incomplete** in general.
 - **Not** all detected errors are **true alarms**.
 - It suffers from **false alarms** (**false positive (FP)**).
 - There is **no missing errors**. We can prove a program is error-free.

- **Dynamic analysis** is **complete** but **unsound** in general.
 - All the detected errors are **true alarms** (**true positive (TP)**).
 - It will not detect any errors in error-free programs.
 - It suffers from **missing errors** (**false negative (FN)**).
- **Static analysis** is **sound** but **incomplete** in general.
 - **Not** all detected errors are **true alarms**.
 - It suffers from **false alarms** (**false positive (FP)**).
 - There is **no missing errors**. We can **prove** a program is error-free.

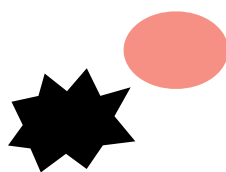
★ : Possible States ● : Error States ⋮ : Dynamic Analysis ⬡ : Static Analysis



P₁



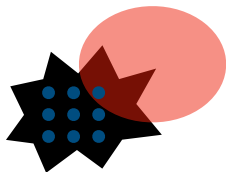
P₂



P₃

- **Dynamic analysis** is **complete** but **unsound** in general.
 - All the detected errors are **true alarms** (**true positive (TP)**).
 - It will not detect any errors in error-free programs.
 - It suffers from **missing errors** (**false negative (FN)**).
- **Static analysis** is **sound** but **incomplete** in general.
 - **Not** all detected errors are **true alarms**.
 - It suffers from **false alarms** (**false positive (FP)**).
 - There is **no missing errors**. We can **prove** a program is error-free.

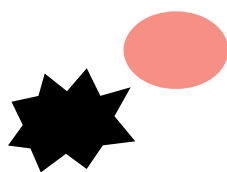
★ : Possible States ● : Error States ●●● : Dynamic Analysis ■ : Static Analysis



P₁

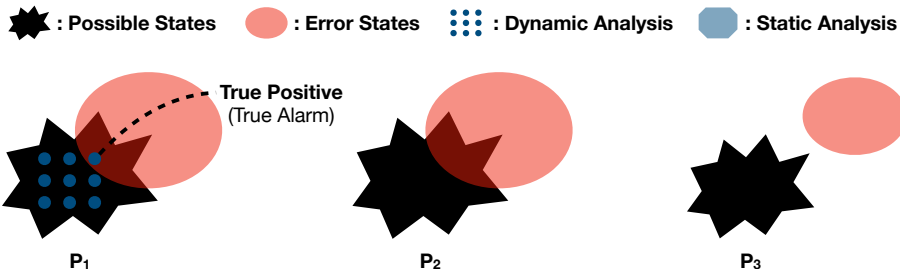


P₂

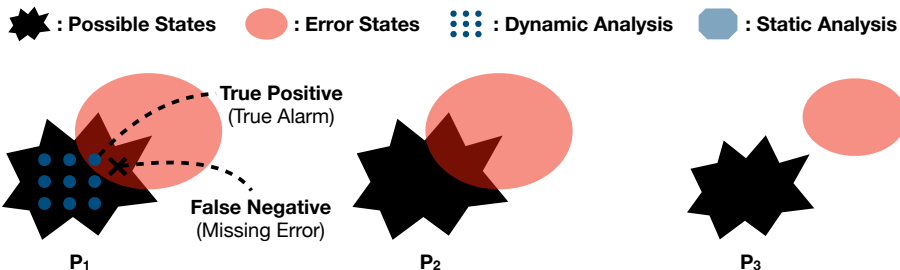


P₃

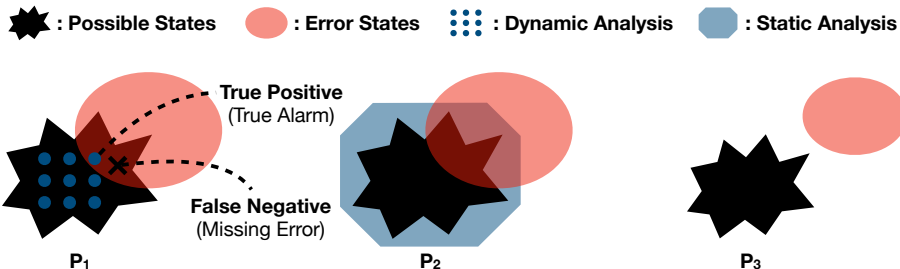
- **Dynamic analysis** is **complete** but **unsound** in general.
 - All the detected errors are **true alarms** (**true positive (TP)**).
 - It will not detect any errors in error-free programs.
 - It suffers from **missing errors** (**false negative (FN)**).
- **Static analysis** is **sound** but **incomplete** in general.
 - **Not** all detected errors are **true alarms**.
 - It suffers from **false alarms** (**false positive (FP)**).
 - There is **no missing errors**. We can **prove** a program is error-free.



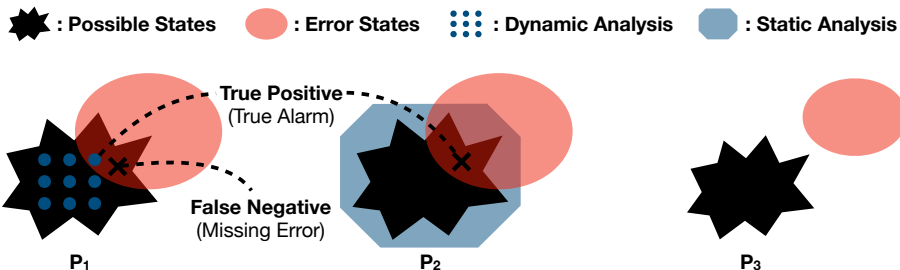
- **Dynamic analysis** is **complete** but **unsound** in general.
 - All the detected errors are **true alarms** (**true positive (TP)**).
 - It will not detect any errors in error-free programs.
 - It suffers from **missing errors** (**false negative (FN)**).
- **Static analysis** is **sound** but **incomplete** in general.
 - **Not** all detected errors are **true alarms**.
 - It suffers from **false alarms** (**false positive (FP)**).
 - There is **no missing errors**. We can **prove** a program is error-free.



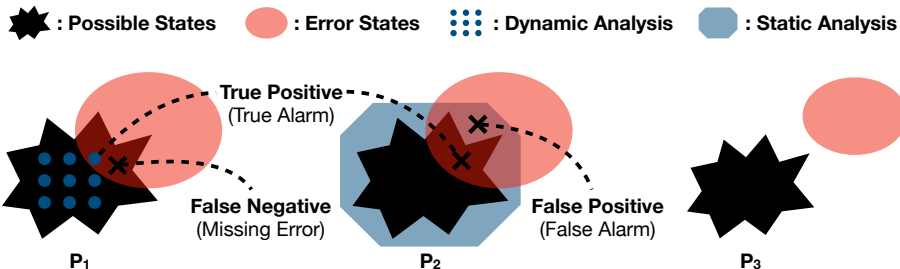
- **Dynamic analysis** is **complete** but **unsound** in general.
 - All the detected errors are **true alarms** (**true positive (TP)**).
 - It will not detect any errors in error-free programs.
 - It suffers from **missing errors** (**false negative (FN)**).
- **Static analysis** is **sound** but **incomplete** in general.
 - **Not** all detected errors are **true alarms**.
 - It suffers from **false alarms** (**false positive (FP)**).
 - There is **no missing errors**. We can **prove** a program is error-free.



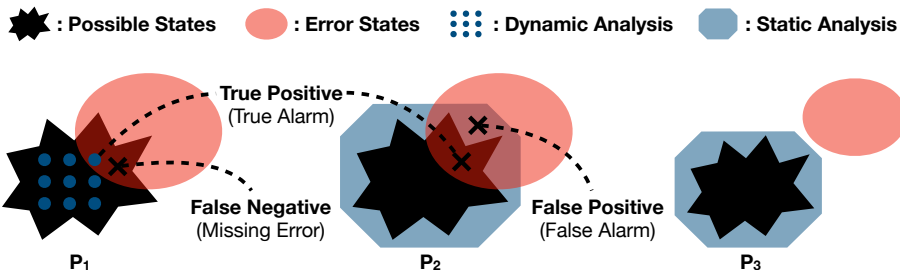
- **Dynamic analysis** is **complete** but **unsound** in general.
 - All the detected errors are **true alarms** (**true positive (TP)**).
 - It will not detect any errors in error-free programs.
 - It suffers from **missing errors** (**false negative (FN)**).
- **Static analysis** is **sound** but **incomplete** in general.
 - **Not** all detected errors are **true alarms**.
 - It suffers from **false alarms** (**false positive (FP)**).
 - There is **no missing errors**. We can **prove** a program is error-free.



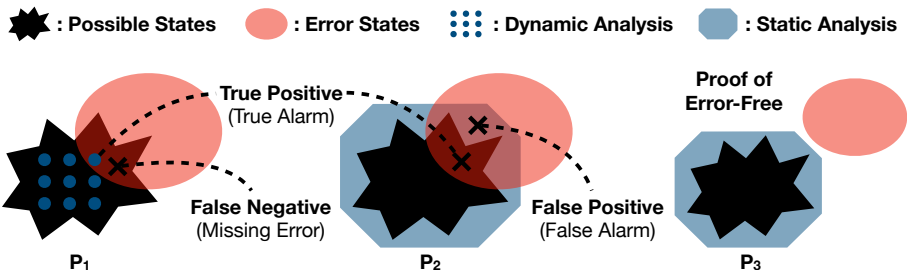
- **Dynamic analysis** is **complete** but **unsound** in general.
 - All the detected errors are **true alarms** (**true positive (TP)**).
 - It will not detect any errors in error-free programs.
 - It suffers from **missing errors** (**false negative (FN)**).
- **Static analysis** is **sound** but **incomplete** in general.
 - **Not** all detected errors are **true alarms**.
 - It suffers from **false alarms** (**false positive (FP)**).
 - There is **no missing errors**. We can **prove** a program is error-free.



- **Dynamic analysis** is **complete** but **unsound** in general.
 - All the detected errors are **true alarms** (**true positive (TP)**).
 - It will not detect any errors in error-free programs.
 - It suffers from **missing errors** (**false negative (FN)**).
- **Static analysis** is **sound** but **incomplete** in general.
 - **Not** all detected errors are **true alarms**.
 - It suffers from **false alarms** (**false positive (FP)**).
 - There is **no missing errors**. We can **prove** a program is error-free.



- **Dynamic analysis** is **complete** but **unsound** in general.
 - All the detected errors are **true alarms** (**true positive (TP)**).
 - It will not detect any errors in error-free programs.
 - It suffers from **missing errors** (**false negative (FN)**).
- **Static analysis** is **sound** but **incomplete** in general.
 - **Not** all detected errors are **true alarms**.
 - It suffers from **false alarms** (**false positive (FP)**).
 - There is **no missing errors**. We can **prove** a program is error-free.



1. Motivation: Safe Language Systems

Detecting Run-Time Errors

Dynamic vs Static Analysis

Soundness vs Completeness

2. Type Systems

Types

Type Errors

Type Checking

Type Soundness

Definition (Types)

A **type** is a set of values.

For example, the `Int`, `Boolean`, and `Int => Int` types are defined as the following sets of values in Scala.

$$\text{Int} = \{n \in \mathbb{Z} \mid -2^{31} \leq n < 2^{31}\}$$

$$\text{Boolean} = \{\text{true}, \text{false}\}$$

$$\text{Int} \Rightarrow \text{Int} = \{f \mid f \text{ is a function from Int to Int}\}$$

```
val n: Int = 42           // 42    : Int
n + 1                   // 43    : Int
val b: Boolean = n > 10   // true  : Boolean
def f(x: Int): Int = x + 1 // f     : Int => Int
f(42)                   // 43    : Int
```

Definition (Type Errors)

A **type error** occurs when a program tries to use a value having a type that is **incompatible** with the expected type.

For example, the following Scala program has type errors:

```
42 + true           // `Int` expected for `+`, but `Boolean` found
if (1) 2 else 3     // `Boolean` expected for `if`, but `Int` found
def f(x: Int): Int = x + 1
f(false)           // `Int` expected for `f`, but `Boolean` found
```

However, not all **run-time errors** are **type errors**:

```
42 / 0              // `ArithmeticException` at run-time
case class A(k: Int)
val x: A = null
x.k                 // `NullPointerException` at run-time
```

If the following conditions hold, we say “**the expression e has type τ** ”:

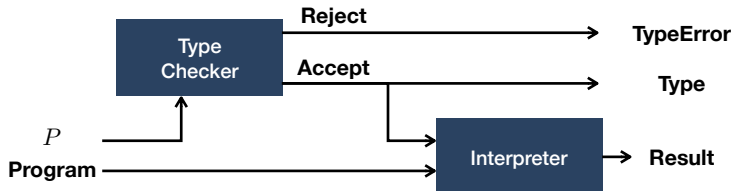
- e does not cause any type error, and
- e evaluates to a value of type τ or does not terminate.

If so, we use the following notation and say that e is **well-typed**:

$$\boxed{\vdash e : \tau}$$

Definition (Type Checking)

Type checking is a kind of static analysis checking whether a given expression e is **well-typed**. A **type checker** returns the **type** of e if it is well-typed, or rejects it and reports the detected **type error** otherwise.



Definition (Type Soundness)

A **type system** is **sound** if it guarantees that a **well-typed** program will **never** cause a **type error** at run-time.

There are two categories of languages in the context of type system:

- **Statically-typed languages** (or simply typed-language) only allow **well-typed** programs to be executed.
(e.g. Java, Scala, Haskell, OCaml, Rust, etc.)
- **Dynamically-typed languages** (or simply untyped-language) allow any program to be executed, and types exist only at run-time.
(e.g. Python, Ruby, JavaScript, etc.)

Type systems in most statically-typed languages are designed to be **sound**.

1. Motivation: Safe Language Systems

- Detecting Run-Time Errors
- Dynamic vs Static Analysis
- Soundness vs Completeness

2. Type Systems

- Types
- Type Errors
- Type Checking
- Type Soundness

- Please see this document¹ on GitHub.
- The due date is Nov. 27 (Mon.).
- Please only submit `Implementation.scala` file to **Blackboard**.

¹<https://github.com/ku-plrg-classroom/docs/tree/main/cose212/magnet>.

- Typed Languages

Jihyeok Park

jihyeok_park@korea.ac.kr

<https://plrg.korea.ac.kr>