Contents

Programming Language Design Workshop

A hands-on course exploring programming language design concepts using Python's modern features. This course leverages Python's type system and structural pattern matching to demonstrate key programming language concepts and implementations.

Course Overview

This workshop consists of 10 lectures (2 hours each) that combine theoretical foundations with practical implementations. Students will learn about programming language design principles while getting hands-on experience with Python's advanced features.

Course Structure

Lecture 1: Introduction to Programming Language Design

- What is a programming language?
- The importance of programming language design
- The course structure and expectations
- Python as a language for exploring language design concepts

Lecture 2: Types and Structural Pattern Matching in Python

- Introduction to Python's type system
- Type hints and type checking
- Structural pattern matching (match/case statements)
- Practical applications and examples

Lecture 3: Programming Language Fundamentals

- What is a programming language?
- Parsing and lexical analysis
- Abstract Syntax Trees (AST)
- Program semantics
- Core language features
- Theoretical foundations

Lecture 3: TBA

Lecture 4: TBA

Lecture 5: TBA

Lecture 6: TBA

Lecture 7: TBA

Lecture 8: TBA

Lecture 9: TBA

Lecture 10: TBA

Prerequisites

- Python 3.10 or higher (for pattern matching support)
- Basic Python programming knowledge
- Understanding of basic programming concepts

Repository Structure

Each lecture has its own directory containing: - A detailed README.md with lecture notes and exercises - Python modules with examples and implementations - Additional resources and references when applicable

Getting Started

1. Clone this repository
2. Ensure you have Python 3.10+ installed
3. Navigate to the specific lecture directory
4. Follow the instructions in each lecture's README.md

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Chapter 1: Programming Language Design and Implementation

Section 1: What is a Programming Language?

- Formal system for instructing computers
- Consists of syntax and semantics
- Bridge between human thought and machine execution
- Examples: Python, Java, C++, JavaScript, FSharp, Haskell, Microsoft Word, Excel, Ableton Live, Mathematica, LaTeX, HTML, CSS, SQL, ...
- Everything is a formal language!

Formal system for instructing computers

A programming language is a formal system for instructing computers to perform specific tasks. It provides a structured way to communicate with machines using a well-defined set of rules and conventions. These languages enable humans to express complex algorithms and computations in a way that computers can understand and execute.

Syntax and semantics

The *syntax* and *semantics* of a programming language form its core components. Syntax refers to the set of rules that define how programs are written, including grammar, punctuation, and structure. For example, in Python, the syntax for arithmetic expressions follows specific rules:

- Operators must be placed between operands: `2 + 3` (valid) vs `+ 2 3` (invalid)
- Parentheses must be balanced: `(2 + 3) * 4` (valid) vs `(2 + 3 * 4` (invalid)
- Operator precedence determines evaluation order: `2 + 3 * 4` evaluates to 14, not 20

Semantics, on the other hand, determines the meaning of these syntactically correct programs and how they behave when executed.

Here's an example of a semantic valuation function for arithmetic expressions:

> `V` is the semantic evaluation function that maps syntactic expressions to their computed values

- Define valuation function `V(expr)`:
  - Input: `expr` (arithmetic expression)
  - Output: integer result
- Handle different expression types:
  - If `expr` is a number:
    - Return the number's value
  - If `expr` is of form `(a + b)`:
    - If `type(V(a))` and `type(V(b))` are numeric: Return `V(a) + V(b)`
    - Else: raise `TypeError`
  - If `expr` is of form `(a - b)`:
    - If `type(V(a))` and `type(V(b))` are numeric: Return `V(a) - V(b)`
    - Else: raise `TypeError`
  - If `expr` is of form `(a * b)`:
    - If `type(V(a))` and `type(V(b))` are numeric: Return `V(a) * V(b)`
    - Else: raise `TypeError`
  - If `expr` is of form `(a / b)`:
    - If `type(V(a))` and `type(V(b))` are numeric:
      - If `V(b) == 0`: raise `DivisionByZeroError`
      - Else: Return `V(a) / V(b)`

        * Else: raise `TypeError`

4. Handle operator precedence:
    - Multiplication and division have higher precedence than addition and subtraction; this is usually decided by the grammar of the language and the parser
    - Parentheses override default precedence; program semantics is responsible for this

Example evaluation: Let's evaluate the expression `(2 + 3) * 4` using our valuation function:

1. Parse the expression into its components:
    - Outer operation: `*`
    - Left operand: `(2 + 3)`
    - Right operand: `4`
2. Evaluate the left operand `(2 + 3)`:
    - Parse the sub-expression:
        - Operation: `+`
        - Left operand: `2`
        - Right operand: `3`
    - Apply the addition rule:
        - `V(2)` returns `2`
        - `V(3)` returns `3`
        - `V(2 + 3)` returns `2 + 3 = 5`
3. Evaluate the right operand `4`:
    - `V(4)` returns `4`
4. Apply the multiplication rule:
    - `V((2 + 3) * 4)` returns `5 * 4 = 20`

Final result: `20`

Bridge between human thought and machine execution

Programming languages serve as a crucial bridge between human thought and machine execution. They allow developers to express abstract ideas and problem-solving strategies in a format that can be translated into machine code. This translation enables computers to perform complex operations and solve real-world problems efficiently.

The world of programming languages is vast and diverse, encompassing general-purpose languages like Python and Java, domain-specific languages like SQL and HTML, and even languages embedded in applications like Microsoft Word macros and Excel formulas. This diversity demonstrates how programming languages have become fundamental tools in virtually every aspect of modern computing.

Everything is a formal language

The concept of formal languages extends beyond traditional programming languages. Everything from mathematical notation to musical scores are formal languages, as they all provide structured systems for expressing and communicating complex ideas in a **machine-executable** format.

Most computer programs have a notion of "document" or "project", which is a collection of files that are used to create a larger work. These documents are essentially formal languages, as they are structured systems for expressing and communicating complex ideas. The user interface of a program helps building these documents (the syntax) and the program itself interprets these documents (the semantics).

This broader perspective helps us understand the fundamental role of formal systems in human-computer interaction and information processing.

Programming language design and the AI era

The advent of artificial intelligence is reshaping the landscape of programming language design in profound ways. As AI systems become more sophisticated, they're influencing both how we design languages and how we interact with them.

Let's first establish a key point: AI enables a conversational programming interface does not mean "no code". Rather, AI can help creating a computer program, which however the human must understand and eventually modify. This is needed to create and execute *unambiguous instructions*.

How can anyone (AI or human) ever prove that it has executed a task correctly, if the task is not well defined?

As an example, the reader can consider ComfyUI, which uses a graph-based, low-code, but still completely formal language to create and execute complex generative AI tasks. See https://www.comfy.org/

Indeed, AI is nevertheless changing the way we program, and therefore, will inevitably also change the landscape of programming language design. Among the things that are changing, we find:

- **AI-Assisted Development**:
  - AI-powered code completion and suggestion tools are becoming integral to modern IDEs
  - AI can help identify potential bugs and suggest optimizations
  - Natural language processing enables **conversational** programming interfaces
- **AI-Driven Language Evolution**:
  - AI can analyze code patterns to suggest language improvements
  - Automated testing of language features and syntax changes
  - AI-assisted language standardization and documentation
- **Future Directions**:
  - Integration of natural language processing into language design
  - **Development of AI-specific type systems and semantics**
  - Creation of languages that can evolve and adapt autonomously <– this was actually suggested by the DeepSeek AI.

As we move forward, the relationship between AI and programming language design will continue to deepen, creating new opportunities and challenges for language designers and developers alike.

But the most fundamental, key consideration is that languages need to be designed for both human and AI comprehension. They serve, and will always serve, as a bridge between human thought and machine execution.

Mathematics, as a prime example of a formal language, has been invented by humans, but it has always been used by both humans and machines; it is a universal language to express and reason about complex ideas.

So will be (more and more declarative, more and more high-level) programming languages, as they will be used by both humans and AI systems to formalise complex processes and avoid ambiguity, which is the key issue for both human-driven and ai-driven process design and execution.

Section 2: Key Design Considerations

- Expressiveness and power
- Imperative or Functional?

- Scoping rules
- Memory management
- Error handling mechanisms

Expressiveness and Power

A language's expressiveness refers to its ability to concisely represent complex ideas and operations. More expressive languages allow developers to achieve more with less code, although this sometimes comes at the cost of readability and maintainability. The power of a language is closely related to its expressiveness, but also includes its computational capabilities and the range of problems it can effectively solve. Modern languages like Python strike a balance between expressiveness and clarity.

Imperative, Functional, Object-Oriented, Declarative, Reactive?

Programming languages can be designed around different paradigms, each with its own strengths and trade-offs. The imperative paradigm focuses on explicit control flow and state changes, while functional programming emphasizes immutability and pure functions. Object-oriented programming organizes code around objects and their interactions, and declarative programming focuses on what to achieve rather than how to achieve it. Reactive (a.k.a. "dataflow") programming deals with data streams and change propagation, making it particularly suitable for modern user interfaces. The choice of paradigm depends on the problem domain, with many modern languages supporting multiple paradigms to provide flexibility in solving different types of problems.

Application domains

Application domains

Programming languages are often designed with specific application domains in mind, tailoring their features and capabilities to particular problem spaces. Some notable examples include:

- **Web Development**:
  - JavaScript/TypeScript: The backbone of modern web development, enabling interactive front-end experiences and server-side applications
  - Svelte: A modern framework for building efficient web applications with a compiler-based approach
  - PHP: Widely used for server-side web development and content management systems
- **Scientific Computing**:
  - Python: With libraries like NumPy, SciPy, and Pandas, it's become a dominant language for data analysis and scientific computing
  - MATLAB: Specialized for numerical computing and matrix operations
  - R: Designed for statistical computing and data visualization
- **AI and Machine Learning**:
  - Python: The de facto language for AI/ML with frameworks like TensorFlow and PyTorch
  - Julia: Gaining popularity for high-performance scientific computing and machine learning
- **Music and Multimedia**:
  - Max/MSP: A visual programming language for music and multimedia
  - Pure Data: An open-source alternative for real-time audio and video processing
  - SuperCollider: A language for audio synthesis and algorithmic composition
- **Mathematical Computing**:
  - Mathematica: A powerful system for symbolic mathematics and technical computing

  - Maple: Another computer algebra system for mathematical problem solving
- **Systems Programming**:
  - C/C++: The foundation for operating systems and performance-critical applications
  - Rust: A modern systems programming language focusing on safety and concurrency
- **Mobile Development**:
  - Swift: Apple's language for iOS and macOS development
  - Kotlin: The preferred language for Android development

Each domain-specific language or framework brings specialized features and abstractions that make it particularly suited for its target application area, while general-purpose languages like Python and Java find use across multiple domains.

Scoping Rules

Scoping rules determine how and where variables and functions are accessible within a program. Lexical (static) scoping, used in most modern languages, determines variable visibility based on the program's structure. Dynamic scoping, less common today, but used in operating system shells, determines visibility based on the program's execution state. Proper scoping rules are crucial for managing complexity, preventing naming conflicts, and supporting modular programming. Python's scoping rules, with their global, nonlocal, and local scopes, provide a good example of how scoping can be implemented effectively.

Memory Management

Memory management is a critical aspect of language design that affects both performance and developer productivity. Languages can be manual (like C), garbage-collected (like Java and Python), or use reference counting (like Python and Swift). The choice of memory management strategy impacts the language's runtime performance, memory safety, and the complexity of writing correct programs. Modern languages often provide automatic memory management while allowing manual control when needed for performance optimization.

Error Handling Mechanisms

Error handling is essential for building robust and reliable software. Languages implement various error handling strategies, including exceptions (like in Python and Java), return codes (like in C), and monadic error handling (like in Haskell). The choice of error handling mechanism affects how easily developers can write correct code and how gracefully programs can recover from unexpected situations. Python's exception handling system (similarly to other object-orientedlanguages), with its try/except blocks and exception hierarchy, is widely regarded as both powerful and intuitive.

Section 3: Language Paradigms

- Imperative (C, Python)
- Object-Oriented (Java, C#)
- Functional (Haskell, Lisp)
- Logical (Prolog)
- Declarative (SQL, VoxLogicA)
- Reactive (React, Svelte, Vue)

Imperative (C, Python)

Imperative programming is one of the most common programming paradigms, focusing on describing how a program operates through a sequence of statements that change a program's

state. Languages like C and Python follow this approach, where developers explicitly specify the steps needed to achieve a result. This paradigm is particularly useful for tasks that require precise control over program flow and memory management. However, it can lead to complex code when dealing with large systems, as the focus on state changes can make reasoning about program behavior more challenging.

```
// Pseudo-code example of imperative programming:
// Calculating factorial

function factorial(n):
    // Initialize a variable to store the result
    result = 1

    // Use a loop to iteratively calculate factorial
    for i from 1 to n:
        result = result * i

    // Return the final calculated value
    return result

// Example usage
number = 5
factorialOfNumber = factorial(number)
print("Factorial of", number, "is", factorialOfNumber)
```

Object-Oriented (Java, C#)

Object-oriented programming (OOP) organizes software design around data, or objects, rather than functions and logic. Languages like Java and C# are built around this paradigm, which emphasizes concepts like encapsulation, inheritance, and polymorphism. OOP is particularly effective for modeling real-world systems and managing complex software projects through modular design. However, it can introduce complexity through deep inheritance hierarchies and can sometimes lead to over-engineering of simple problems.

```
// Pseudo-code example of object-oriented programming with subclassing

class Animal:
    // Base class with common attributes and methods
    name: String
    age: Integer

    constructor(name, age):
        this.name = name
        this.age = age

    method makeSound():
        print("Generic animal sound")

    method describe():
        print("Name:", this.name, "Age:", this.age)

class Dog(Animal):
    // Subclass inheriting from Animal
    breed: String
```

```
    constructor(name, age, breed):
        // Call parent constructor
        super(name, age)
        this.breed = breed

    // Override parent method
    method makeSound():
        print("Woof! Woof!")

    method describe():
        // Extended description specific to Dog
        super.describe()
        print("Breed:", this.breed)

// Example usage
myDog = Dog("Buddy", 3, "Labrador")
myDog.describe()    // Prints dog's details
myDog.makeSound()   // Prints dog-specific sound
```

Functional (Haskell, Lisp)

Functional programming treats computation as the evaluation of mathematical functions and avoids changing-state and mutable data. Languages like Haskell and Lisp embody this paradigm, emphasizing pure functions, immutability, and higher-order functions. This approach can lead to more predictable and testable code, as functions with no side effects are easier to reason about. However, it can be challenging for developers accustomed to imperative programming and may require a different way of thinking about problem-solving.

```
// Pseudo-code example of functional programming with immutability and higher-order functi

// Pure function: deterministic and without side effects
let square(x) -> Number:
    return x * x

// Higher-order function: transforms a list using a given function
let map(list, transform) -> List:
    match list:
        | Empty -> []
        | [Head | Tail] ->
            [transform(Head)] ++ map(Tail, transform)

// Immutable data and functional transformation
let numbers = [1, 2, 3, 4, 5]
let squaredNumbers = map(numbers, square)

// Function composition as a first-class operation
let compose(f, g) -> Function:
    return λx: f(g(x))

// Recursive function using tail-call optimization
let factorial(n, accumulator = 1) -> Number:
    match n:
        | 0 -> accumulator
```

```
        | _ -> factorial(n - 1, n * accumulator)

// Functional application demonstrating composition
let result = compose(square, factorial)(3)  // Computes factorial then squares
```

Logical (Prolog)

Logical programming is based on formal logic, where programs consist of a set of facts and rules. Prolog is the most well-known language in this paradigm, where computation is performed by querying these facts and rules. This approach is particularly useful for problems involving symbolic computation, artificial intelligence, and knowledge representation. However, it can be less efficient for general-purpose programming tasks and may require a different mindset from traditional programming approaches.

```
// Pseudo-code example of logical programming with Prolog

// Facts about family relationships
// Facts about family relationships
parent(john, mary).
parent(john, tom).
parent(mary, alice).

// Rules for determining family relationships
grandparent(X, Z) :- parent(X, Y), parent(Y, Z).
sibling(X, Y) :- parent(P, X), parent(P, Y), X \= Y.
```

Declarative (SQL)

Declarative programming focuses on what the program should accomplish rather than how to achieve it. Languages like SQL follow this paradigm, where developers specify the desired results rather than the step-by-step process to achieve them. This approach can lead to more concise and maintainable code, especially for data manipulation and querying tasks. However, it may provide less control over the underlying implementation details and can be less suitable for tasks requiring precise control over program execution. This does *not* mean that declarative programming is “less efficient”; quite the opposite, an SQL *query execution plan* can be highly optimised by the database engine, and be way more efficient than handwritten code.

See also the voxlogica project: http://www.voxlogica.org

```
-- Pseudo-code example of declarative programming with SQL

-- Define a table for employees
CREATE TABLE employees (
    id INTEGER PRIMARY KEY,
    name VARCHAR(100),
    department VARCHAR(50),
    salary DECIMAL(10, 2),
    hire_date DATE
);

// Insert sample records
INSERT INTO employees (name, department, salary, hire_date) VALUES
    ('John Doe', 'Engineering', 75000.00, '2022-01-15'),
    ('Jane Smith', 'Marketing', 65000.50, '2021-11-03');
```

```
// Example query to demonstrate declarative programming
SELECT name, department, salary
FROM employees
WHERE department = 'Engineering'
ORDER BY salary DESC;
```

Reactive (React, Svelte, Vue)

Reactive programming is a paradigm that focuses on data flows and the propagation of change. Languages and frameworks like React, Svelte, and Vue implement this approach, where the UI automatically updates in response to changes in the underlying data. This paradigm is particularly effective for building modern web applications and user interfaces, as it simplifies the management of complex state changes and UI updates. Reactive programming often uses concepts like observables, streams, and declarative bindings to create responsive and efficient applications. While powerful for UI development, it can introduce complexity in managing state across large applications and may require specific architectural patterns to maintain code organization.

```
<script>
    let count = 0;
    $: doubled = count * 2;

    function increment() {
        count += 1;
    }
</script>

<button on:click={increment}>
    Count: {count} (Doubled: {doubled})
</button>
```

Section 4: Implementation Concerns

- Compilation vs. Interpretation
- Memory management
- Garbage collection
- Runtime environment
- Performance optimization

Compilation vs. Interpretation

The choice between compilation and interpretation is a fundamental decision in language implementation. Compiled languages (like C and Rust) translate source code into machine code before execution, resulting in faster runtime performance but requiring a separate compilation step. Interpreted languages (like Python and JavaScript) execute code directly through an interpreter, enabling faster development cycles and platform independence but typically with slower execution speeds. Many modern languages (like Java and C#) use a hybrid approach, compiling to an intermediate bytecode that is then interpreted or just-in-time (JIT) compiled, offering a balance between performance and flexibility.

Memory Management

Memory management is crucial for both performance and safety in programming languages. Manual memory management, as seen in C and C++, gives developers fine-grained control but increases the risk of memory leaks and segmentation faults. Automatic memory management through garbage collection, used in Java and Python, simplifies development by automatically reclaiming unused memory but can introduce unpredictable pauses in program execution. Reference counting, another automatic approach used in Python and Swift, provides more predictable memory reclamation but can struggle with circular references.

Garbage Collection

Garbage collection is a critical component of automatic memory management, responsible for reclaiming unused memory. Different garbage collection algorithms (like mark-and-sweep, generational, and reference counting) offer various trade-offs between throughput, latency, and memory efficiency. Languages like Java and C# use sophisticated garbage collectors that can be tuned for specific workloads, while languages like Go use concurrent garbage collection to minimize pause times. The choice of garbage collection strategy significantly impacts a language's performance characteristics and suitability for different application domains, from real-time systems to long-running server applications.

Runtime Environment

The runtime environment provides essential services for program execution, including memory management, type checking, and security features. Managed runtime environments, like the Java Virtual Machine (JVM) and .NET Common Language Runtime (CLR), offer platform independence and additional safety features but introduce overhead. Native runtime environments, as used in C and Rust, provide direct access to system resources but require more careful programming. Modern runtime environments often include features like just-in-time compilation, dynamic optimization, and extensive standard libraries to improve performance and developer productivity.

A special mention goes to HTML5, the latest version of the Hypertext Markup Language, which provides a runtime environment for web applications. It includes features like local storage, web workers, and web sockets, enabling developers to create more powerful and responsive web applications. HTML5 also supports offline applications, multimedia, and advanced graphics, making it a versatile runtime environment for modern web development and also for desktop applications, thanks to frameworks such as Electron or Tauri.

Performance Optimization

Performance optimization in programming languages involves various techniques at different levels of the implementation stack. Compiler optimizations, such as inlining, loop unrolling, and dead code elimination, can significantly improve execution speed without changing the source code. Runtime optimizations, like JIT compilation and adaptive optimization, can dynamically improve performance based on actual usage patterns. Language designers must balance optimization opportunities with compilation speed, memory usage, and the complexity of the implementation. Modern languages often provide profiling tools and optimization flags to help developers identify and address performance bottlenecks in their code.

Section 5: Syntax and Semantics

- Syntax: Rules for valid program structure
- Semantics: Meaning of valid programs

- Abstract Syntax Trees (AST)
- Context-free grammars
- Parsing techniques

Syntax: Rules for valid program structure

Syntax defines the formal rules that govern how programs are written in a language. It specifies the valid combinations of symbols, keywords, and structures that constitute a well-formed program. Syntax rules are typically defined using formal grammars, such as context-free grammars, which provide a precise specification of the language's structure. These rules determine everything from basic elements like variable declarations and function definitions to more complex constructs like control flow statements and class definitions. While syntax rules are often rigid, many modern languages include syntactic sugar - features that make the language more expressive and easier to use without changing its fundamental capabilities.

Semantics: Meaning of valid programs

Semantics defines the meaning of syntactically valid programs - what happens when a program is executed. While syntax determines whether a program is well-formed, semantics determines what the program actually does. There are different approaches to defining semantics, including operational semantics (describing how a program executes), denotational semantics (mapping programs to mathematical objects), and axiomatic semantics (describing program behavior through logical assertions). Understanding semantics is crucial for writing correct programs, as it helps developers predict how their code will behave and ensures that programs produce the intended results.

Context-free grammars

Context-free grammars (CFGs) are formal systems used to describe the syntax of programming languages. They consist of a set of production rules that define how symbols in the language can be combined. CFGs are particularly useful because they can be parsed efficiently and provide a clear, mathematical foundation for language design. They consist of terminal symbols (the actual characters/tokens in the language), non-terminal symbols (abstract syntactic categories), and production rules (how non-terminals can be expanded into sequences of terminals and other non-terminals). While CFGs are powerful, some language features (like indentation-sensitive syntax in Python) require extensions to the basic CFG model.

Parsing techniques

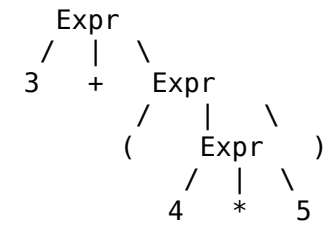
Parsing is the process of analyzing a sequence of tokens to determine its grammatical structure according to a given formal grammar. There are several parsing techniques used in language implementation, including top-down parsing (like recursive descent) and bottom-up parsing (like LR parsing). Top-down parsers build the parse tree from the root down to the leaves, while bottom-up parsers work from the leaves up to the root. Modern language implementations often use parser generators (like ANTLR or Yacc) that can automatically generate efficient parsers from a grammar specification. The choice of parsing technique can affect both the performance of the language implementation and the complexity of the grammar that can be supported.

Abstract Syntax Trees (AST)

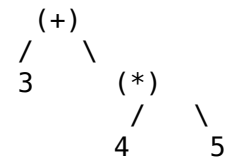
An Abstract Syntax Tree (AST) is a tree representation of the syntactic structure of source code. It abstracts away from the concrete syntax (like punctuation and specific keywords) and

focuses on the essential structure of the program. ASTs are used extensively in compilers and interpreters, as they provide a convenient intermediate representation for performing various transformations and analyses. Each node in the tree represents a construct occurring in the source code, with the children of the node representing its components. ASTs are particularly useful for implementing features like syntax highlighting, code formatting, and static analysis tools.

Example of a parse tree:



Example of an AST:



Normally there is a translation step between the parse tree and the AST.

Section 6: Type Systems

- Static vs. Dynamic typing
- Strong vs. Weak typing
- Type inference
- Type safety
- Generics and polymorphism
- Union and intersection types

Static vs. Dynamic typing

Static typing requires variable types to be explicitly declared and checked at compile time, while dynamic typing determines types at runtime. Statically typed languages like Java and C++ provide early error detection and better tooling support, but can be more verbose. Dynamically typed languages like Python and JavaScript offer more flexibility and faster development cycles, but may lead to runtime errors that could have been caught earlier. The choice between static and dynamic typing often depends on the project's requirements and the development team's preferences.

```java
// Example of static typing in Java
public class Main {
    public static void main(String[] args) {
        // Explicit type declaration required
        int number = 42;          // 'number' is statically typed as int
        String text = "Hello";    // 'text' is statically typed as String

        // Type checking at compile time
        // number = "Hello";      // This would cause a compile-time error
        // text = 42;            // This would also cause a compile-time error
```

```
        System.out.println(number + " " + text);
    }
}
```

```python
# Example of dynamic typing in Python
def main():
    # No explicit type declaration
    value = 42          # 'value' is initially an integer
    print(type(value))  # Output: <class 'int'>

    value = "Hello"     # 'value' is now a string
    print(type(value))  # Output: <class 'str'>

    value = 3.14        # 'value' is now a float
    print(type(value))  # Output: <class 'float'>

if __name__ == "__main__":
    main()
```

Strong vs. Weak typing

Strong typing enforces strict type rules and prevents implicit type conversions, while weak typing allows more flexible type handling. Strongly typed languages like CSharp, Java, FSharp and Haskell help prevent type-related bugs and make code more predictable, but can require more explicit type conversion code. Weakly typed languages like JavaScript and PHP can be more convenient for quick scripting but may lead to unexpected behavior due to implicit type coercion. The strength of a type system affects how easily developers can reason about code behavior and maintain type safety.

A modern trend in language design is to delegate strong type checking to the editor, which highlights type errors at compile time. This is in contrast to languages like C# or Java, where the compiler performs the type checking. A poorly typed program will still run, which may be a balanced choice for development. Note that industrial programming environments also require programmers to write unit tests, which can help catch errors, and also in that case, programs can be executed (e.g. for debugging) also when tests are not passing. Typing-in-the-editor is somehow aligned to testing in this respect.

Type inference

Type inference allows the compiler to automatically deduce types based on context, reducing the need for explicit type annotations. Languages like Haskell use sophisticated type inference systems that can often determine types without explicit declarations. This feature combines the benefits of static typing with the convenience of dynamic typing, making code more concise while maintaining type safety. However, complex type inference can sometimes make error messages harder to understand and may require explicit type annotations in certain cases.

Generics and polymorphism

Generics allow writing code that works with multiple types while maintaining type safety, while polymorphism enables objects to take on multiple forms. Languages like Java and C#, and functional languages like OCaml, Haskell, FSharp, use generics to create reusable, type-safe components, while polymorphism allows for more flexible and extensible designs. These features help reduce code duplication and create more maintainable systems, but can introduce

complexity in understanding and implementing type hierarchies and generic constraints.

Union and intersection types

Union types allow a value to be one of several types, while intersection types combine multiple types into one. Languages like TypeScript and Python's type system support these advanced type features, enabling more precise type definitions and better code documentation. Union types are particularly useful for handling multiple possible input types, while intersection types can describe objects that must satisfy multiple interfaces. These features enhance type safety and expressiveness but can increase the complexity of type checking and inference. Nevertheless, the expressivity of such type systems provides a strong foundational alternative to object-oriented programming, often resulting in more maintainable and scalable systems.

Section 7: Modern Language Trends

- Concurrency and parallelism
- Functional programming features
- Type inference and safety
- Domain-specific languages
- Interoperability with other languages

Concurrency and Parallelism

Modern programming languages are increasingly focusing on concurrency and parallelism to handle the demands of multi-core processors and distributed systems. Concurrency allows multiple tasks to make progress simultaneously, while parallelism enables the execution of multiple tasks at the same time. Languages like Go and Rust have built-in support for concurrent programming through goroutines and async/await patterns, respectively. These features help developers write efficient, scalable applications that can take full advantage of modern hardware. However, managing shared state and avoiding race conditions remain significant challenges in concurrent programming, requiring careful design and the use of synchronization primitives.

Asynchronous programming

Asynchronous programming has become a crucial feature in modern languages to handle I/O-bound operations and improve application responsiveness. Languages like JavaScript, Python, and C# provide async/await syntax to write asynchronous code that appears synchronous, making it easier to reason about and maintain. This approach allows programs to perform non-blocking operations, such as network requests or file I/O, without freezing the user interface or wasting CPU cycles, and at the same time avoiding the pitfalls and complexity of parallel semantics. Asynchronous programming models help create more efficient and responsive applications, particularly in web development and server-side programming, where handling multiple concurrent requests is essential. However, managing asynchronous code flow and error handling can introduce complexity, requiring careful design and the use of appropriate patterns and libraries.

Functional Programming Features

Functional programming concepts are being incorporated into many mainstream languages, bringing benefits like immutability, pure functions, and higher-order functions. Languages like Python, JavaScript, and C# now support features such as structured types, lambda expressions, map/filter/reduce operations, and pattern matching. These features enable developers

to write more concise, declarative code and can lead to programs that are easier to reason about and test. The adoption of functional programming principles also promotes better code organization and can help reduce side effects, leading to more predictable program behavior.

Type Inference and Safety

Type systems in modern languages are becoming more sophisticated, with features like type inference reducing the need for explicit type annotations while maintaining type safety. Languages like TypeScript and Swift use type inference to automatically determine types based on context, making code more concise without sacrificing safety. Advanced type systems also include features like algebraic data types, type classes, and dependent types, which can catch more errors at compile time. These developments help create more robust software by preventing common runtime errors and making code more self-documenting.

Domain-Specific Languages

Domain-specific languages (DSLs) are specialized programming languages designed for particular application domains. They offer higher-level abstractions and more expressive syntax for specific tasks, such as SQL for database queries or HTML for web page structure. Modern language design often includes facilities such as Algebraic Data Types (ADTs) or Monadic syntax (see also computation expressions in FSharp), for creating embedded DSLs within general-purpose languages, allowing developers to create custom syntax and semantics tailored to their specific needs. This approach combines the power of general-purpose programming with the convenience and expressiveness of domain-specific solutions.

Interoperability with Other Languages

As software systems become more complex, the ability to interoperate with code written in other languages has become increasingly important. Many modern languages provide foreign function interfaces (FFIs) or support for calling functions from other languages. For example, Python's C API allows integration with C/C++ code, while WebAssembly enables running code from multiple languages in web browsers. This interoperability allows developers to leverage existing libraries and frameworks while still using their preferred language for new development, promoting code reuse and reducing development time.

Lecture 1: Types and Pattern Matching in Python

This lecture introduces two powerful features of modern Python: the type system and structural pattern matching. These features not only make Python code more robust and maintainable but also serve as excellent examples of programming language design concepts.

Learning Objectives

- Understand Python's type system and type hints
- Master structural pattern matching with match/case statements
- Learn about type checking and its benefits
- Apply these concepts in practical examples

Type System

Static Type Hints

- Introduction to type annotations
- Built-in types: `int`, `str`, `list`, `dict`, etc.
- Complex types: `Union`, `Optional`, `Any`
- Generic types and type variables
- Custom types and `TypeVar`

Type Checking

- Using `mypy` for static type checking
- Runtime type checking considerations
- Type checking best practices
- Common type-related errors and how to fix them

Structural Pattern Matching

Basic Pattern Matching

- Introduction to `match` statement
- Simple patterns with literals
- Variable patterns
- Wildcard patterns (`_`)

Advanced Patterns

- Sequence patterns
- Mapping patterns
- OR patterns (`|`)
- Guard clauses (`if`)
- Class patterns

Practical Examples

The accompanying Python module `types_and_matching.py` contains practical examples demonstrating: 1. Type hints in function definitions 2. Generic type usage 3. Pattern matching for data processing 4. Combining types and pattern matching

Exercises

1. Implement a function that uses type hints and processes different data structures
2. Create a pattern-matching based calculator
3. Design a small type-safe data processing pipeline

Additional Resources

- Python Type Checking Guide
- PEP 484 – Type Hints
- PEP 634 – Structural Pattern Matching

Lecture 2: Parsing with Parsimonious

This lecture covers parsing concepts using the Parsimonious library, a pure-Python PEG parser library that makes it easy to write clean, maintainable parsers.

Overview

- Introduction to Parsing Expression Grammars (PEG)
- Working with Parsimonious
- Building a practical parser
- Understanding grammar rules and visitors

Requirements

- Python 3.12
- parsimonious

Running the Examples

```
pip install parsimonious
python parsing_examples.py
```