# Lecture 3:
# Storage Management


# Logistics

- Point Solutions App
  - Session ID: **database**
- Difference between 4420 and 6422 sections
  - Advanced lectures
  - Papers (around 9 papers)
  - Advanced questions related to the papers/lectures in exams
- Assignment 1 released on Gradescope
- Due dates on Ed

# Recap

- Tour of relational operators
- BuzzDB
- Why C++?

# Lecture Overview

- Periodic Table
- Storage Management
- Tuple and Field classes
- Generalized Tuple class
- Smart pointers

# Periodic Table of System Design Principles

**Towards a Periodic Table of Computer System Design Principles**

JOY ARULRAJ, Georgia Institute of Technology

System design is often taught through domain-specific solutions specific to particular domains, such as databases, operating systems, or computer architecture, each with its own methods and vocabulary. While this diversity is a strength, it can obscure cross-cutting principles that recur across domains. This paper proposes a preliminary "periodic table" of system design principles distilled from several domains in computer systems. The goal is a shared, concise vocabulary that helps students, researchers, and practitioners reason about structure and trade-offs, compare designs across domains, and communicate choices more clearly. For supporting materials and updates, please refer to the repository at: https://github.com/jarulraj/periodic-table.

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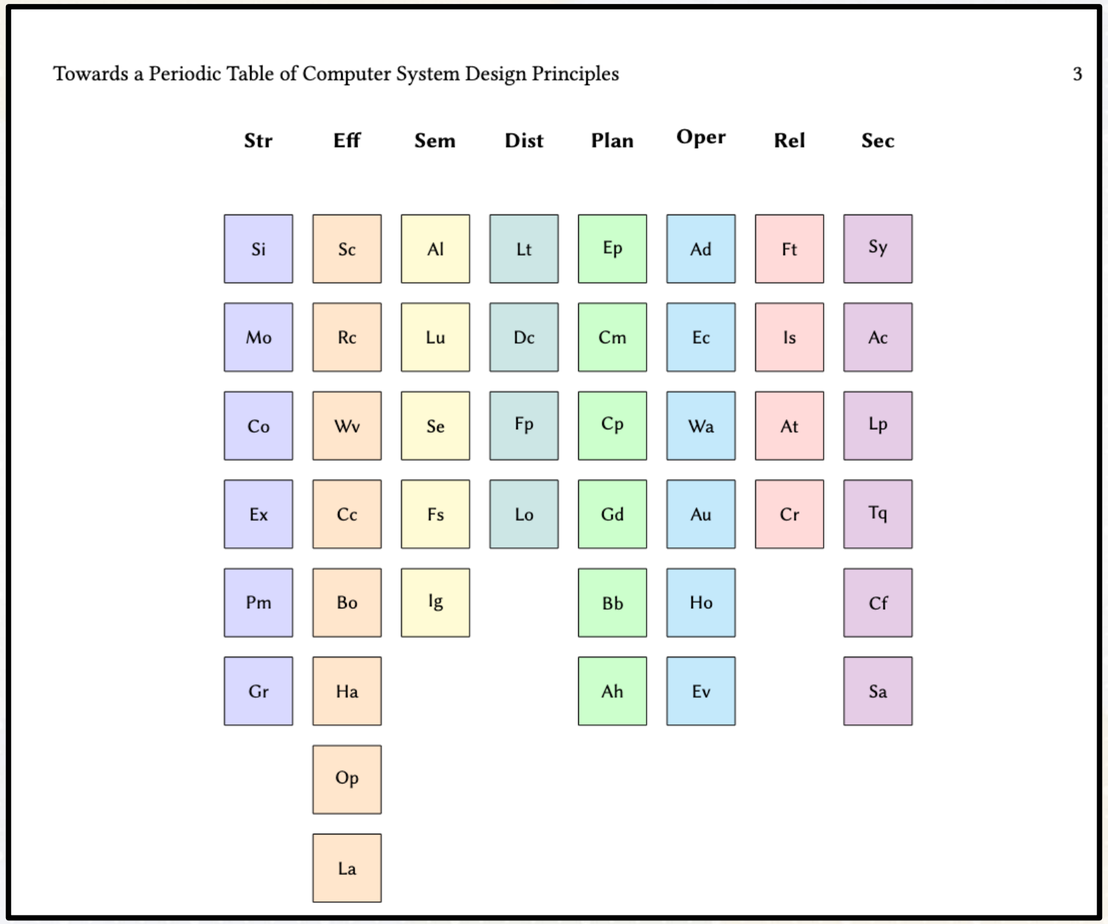
# Periodic Table of System Design Principles



Towards a Periodic Table of Computer System Design Principles 3

| Str | Eff | Sem | Dist | Plan | Oper | Rel | Sec |
|---|---|---|---|---|---|---|---|
| Si | Sc | Al | Lt | Ep | Ad | Ft | Sy |
| Mo | Rc | Lu | Dc | Cm | Ec | Is | Ac |
| Co | Wv | Se | Fp | Cp | Wa | At | Lp |
| Ex | Cc | Fs | Lo | Gd | Au | Cr | Tq |
| Pm | Bo | Ig | | Bb | Ho | | Cf |
| Gr | Ha | | | Ah | Ev | | Sa |
| | Op | | | | | | |
| | La | | | | | | |

# Periodic Table of System Design Principles

- 🟪 **Mo – Modularity**
- Partition the system into cohesive units with minimal interfaces, so that each unit can be reasoned about, replaced, or evolved independently. This principle focuses on decomposition: choosing boundaries to favor clear separation of concerns so that each responsibility sits in one module.
- **Example:** The OSI model decomposes communication into standardised layers with well-defined boundaries that permit independent development and substitution [48].

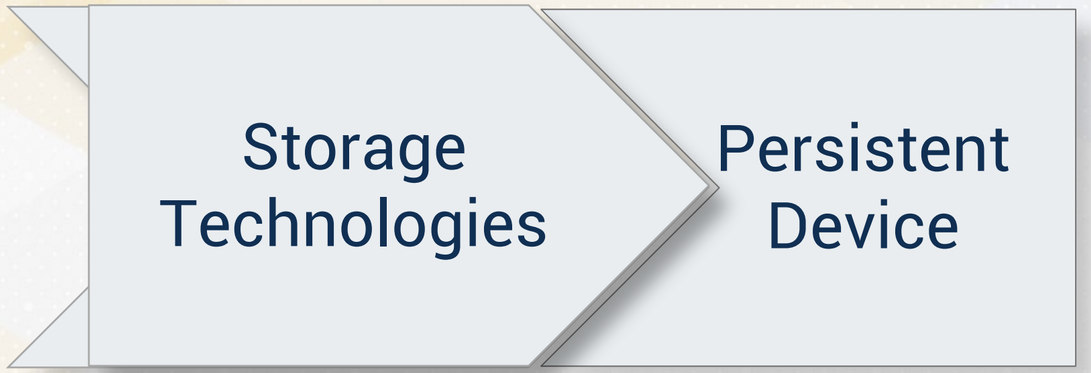
# Periodic Table of System Design Principles

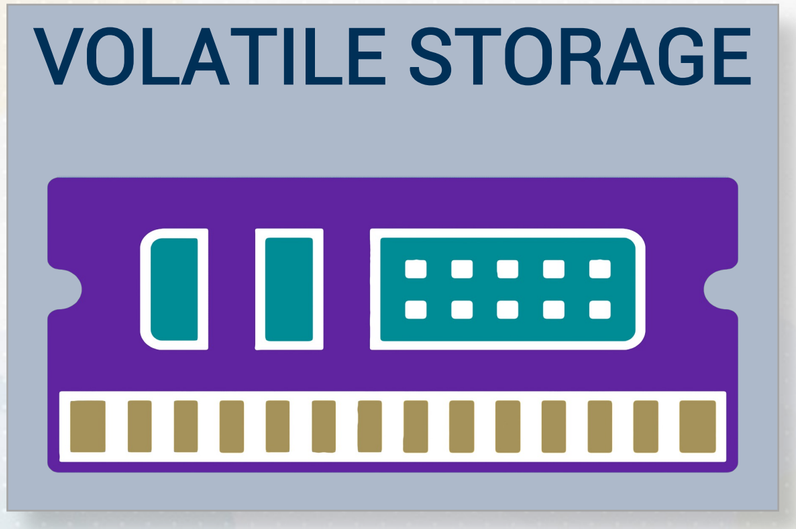
- 🟪 **Co – Composability**
- Design components that can be safely and flexibly recombined; rely on explicit contracts and type-constrained interfaces so that every legal composition remains correct, letting components be assembled like interchangeable bricks. Unlike modularity, this principle focuses on re-composition: making sure the components can be combined safely and flexibly.
- **Example:** Unix programs (e.g., grep, sort, uniq) read from stdin and write to stdout, letting the user compose complex text processing pipelines [41].

# Periodic Table of System Design Principles

- 🟪 **Pm – Policy/Mechanism Separation**
- Separate what should be done (policy) from how it is carried out (mechanism) by exposing a common interface through which multiple policies can plug into the same mechanism.
- **Example:** Hydra has a kernel of generic mechanisms (scheduling, paging, protection) and moved resource-allocation policies to user-level modules [32].

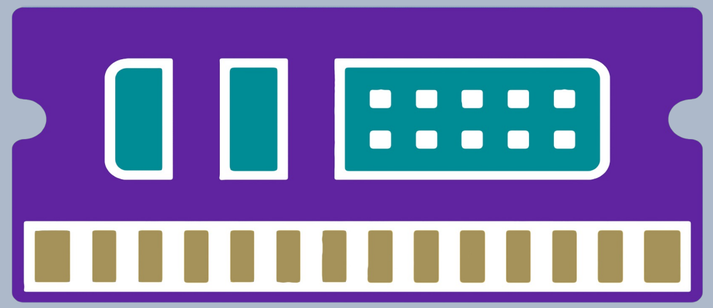
# Storage Technologies




# Volatile Storage

## VOLATILE DRAM

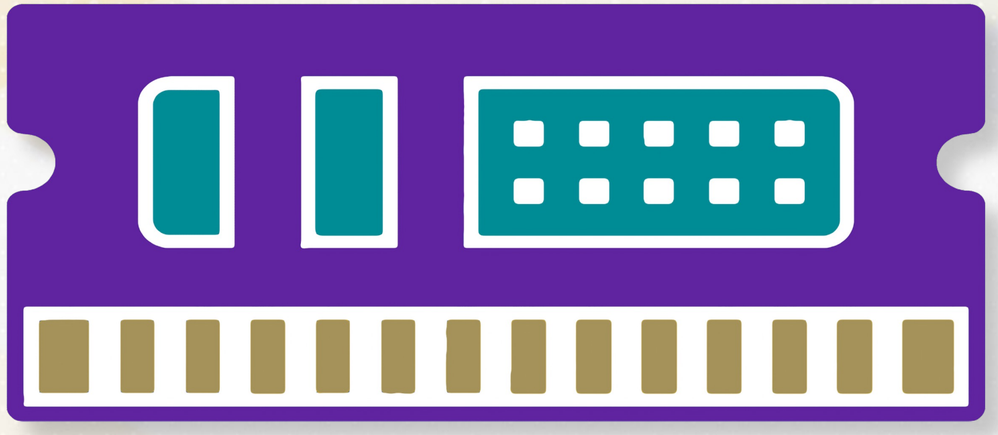


DRAM
(Dynamic Random-Access Memory)

Ideal for Quick Data Access

Data Lost Without Power

# Persistent Storage



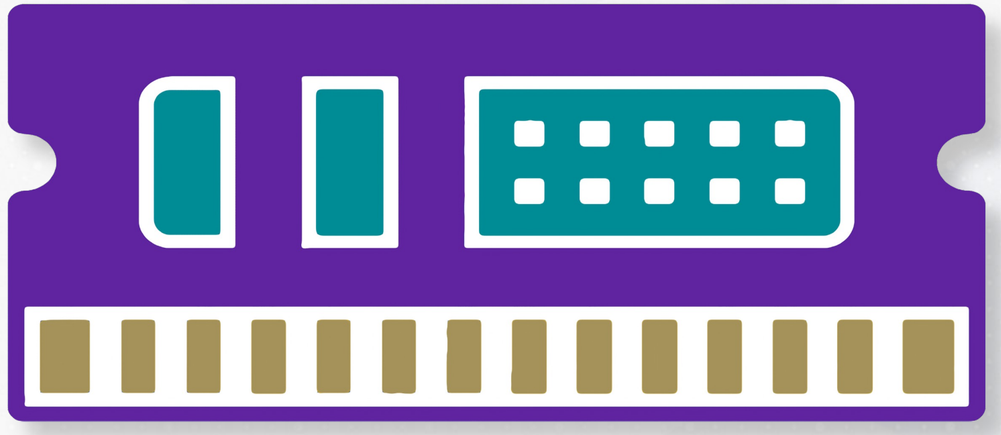
**A** Atomicity

**C** Consistency

**I** Isolation

**D** Durability

# Data Lifecycle: Stage One



“Hot Data” Storage

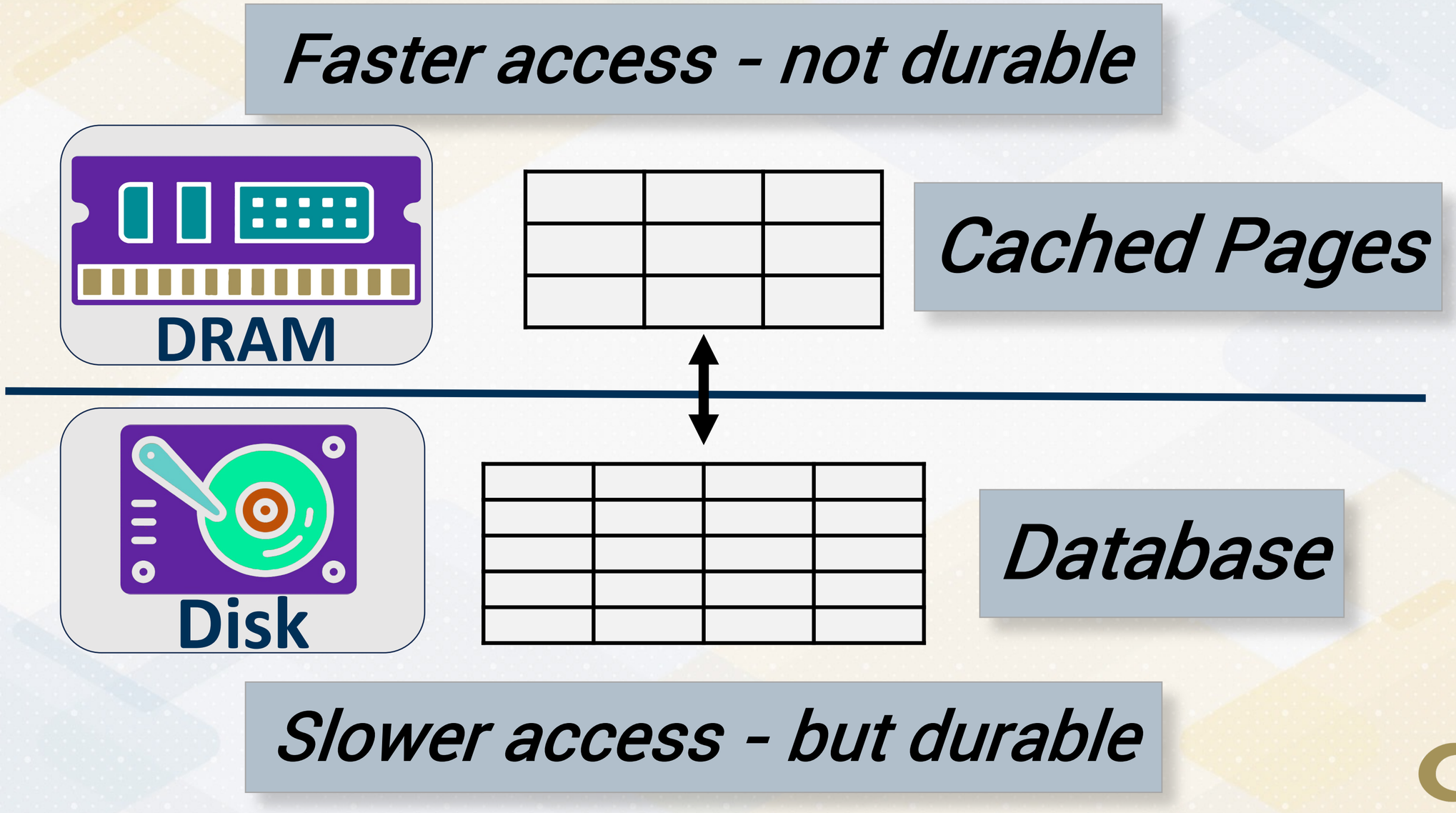
es &
es

# Data Lifecycle: Stage Two

Speed & Durability

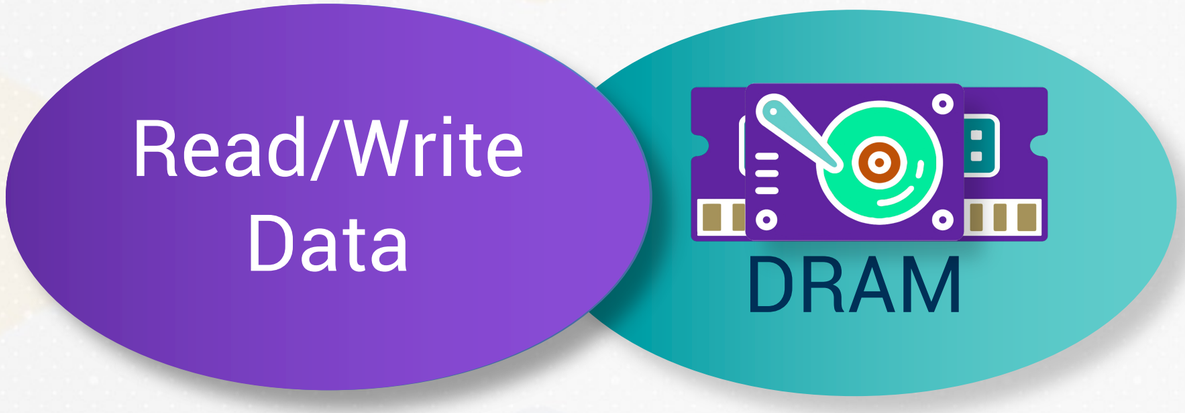
ecure

# Data Lifecycle



# FILE I/O IN C++

# File I/O in C++



# File I/O in C++

buzzDB


```
int main() {
  BuzzDB db;
  // Import data from “output.txt” file
  std::ifstream inputFile("output.txt");
  // Attempt to open file
  int field1, field2;
  // Read pairs of integers from the file and insert them into
BuzzDB
  while (inputFile >> field1 >> field2) {
    db.insert(field1, field2);
  }
  // Perform aggregation query on the imported data
  db.selectGroupBySum();
}
```

# File I/O in C++

Verify File Availability

Use std::cerr Stream

Avoids Data Disruption

```
std::ifstream inputFile("output.txt"); // Attempt to open file

if (!inputFile) {
  std::cerr << "Unable to open file" << std::endl; // Error handling
  return 1;
}
```

# Query Performance in C++

C++ Chrono Library ficiency

```
// Get the start time
auto start = std::chrono::high_resolution_clock::now();
BuzzDB db;
...
db.selectGroupBySum();
// Get the end time
auto end = std::chrono::high_resolution_clock::now();
// Calculate the difference between end and start times
std::chrono::duration<double> elapsed = end - start;
// Output the elapsed time in seconds
std::cout << "Elapsed time: " << elapsed.count() << " seconds" <<
std::endl;
```

# Why does timing matter?

Optimizes Database Operations

Benchmark BuzzDB Performance

# Tuple and Field Classes

# Tuple Class

| Integer Key-Value Pairs | Strings |
| --- | --- |

```
class Tuple {
public:
   // Identifier field
    int key;
    // Actual data field
    int value;
};
```

# Field Class

Field Class

Type

FieldType

INT & FLOAT

Enums

Defines Constants

```
enum FieldType {INT, FLOAT}

class Field {
    public:
    FieldType type;
    union {
        int i;
        float f;
    } data;
};
```

# Field Class

Field Class

Integer I
Float F

Unions

Memory
Share

Field Object

Memory
Allocation

INT & FLOAT

4 Bytes
Storage

```
enum FieldType {INT, FLOAT}

class Field {
    public:
    FieldType type;
    union {
        int i;
        float f;
    } data;
};
```

# Field Class

Integer Value INT

Float Value FLOAT

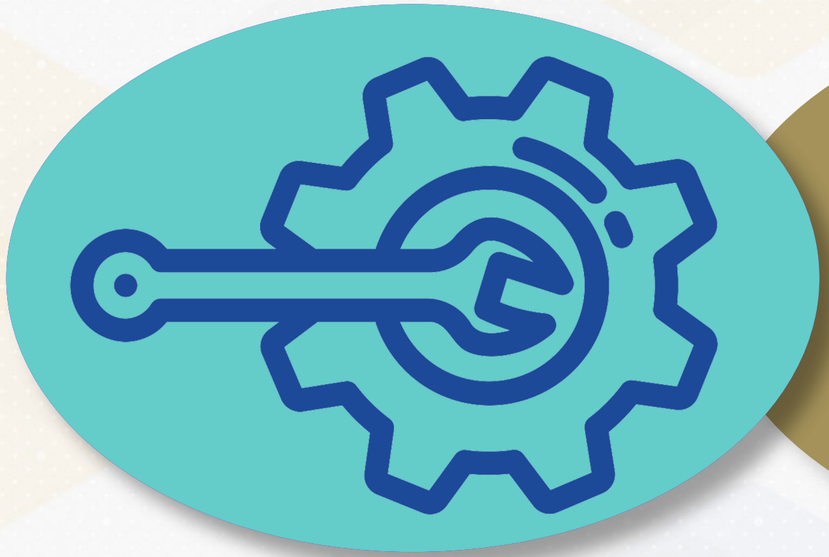
Constructor Overloading

Print Method

```
class Field {
    public:
    Field(int i): type(INT), data{i} {}
    Field(float f): type(FLOAT), data{f} {}
    void print() const {
        switch(type) {
            case INT: std:: cout << data.i;
            break;
            case FLOAT: std:: cout << data.f;
            break;
        }
    }
}
```

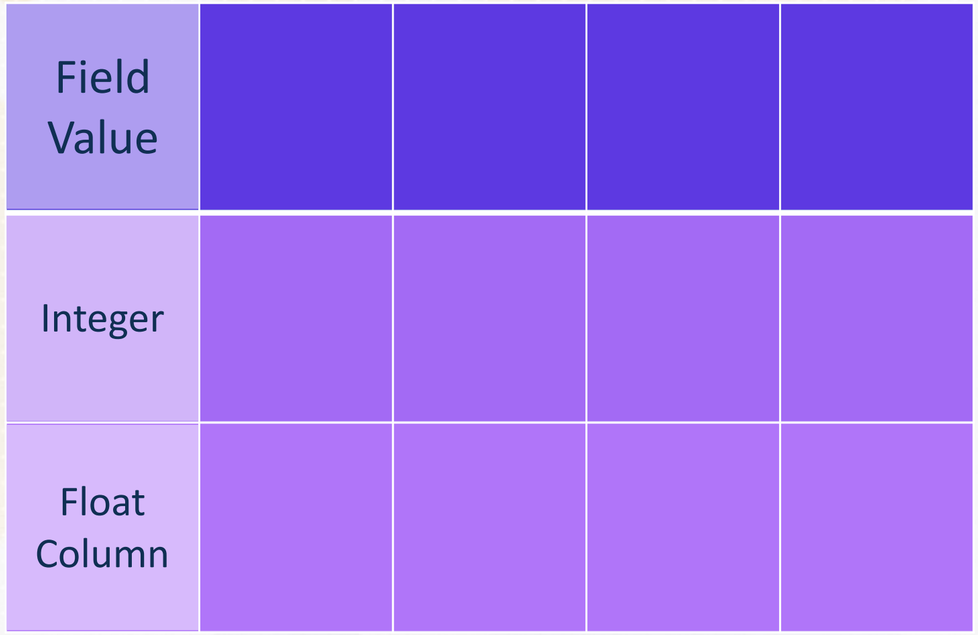
# C++ Constructors, Tuples, and Strings

# Constructors in C++



Initializes Integer
& Float Data

# Generalized Tuple Class




```
class Tuple {
    std::vector<Field> fields;
    public:
    void addField(const Field & field) {
        fields.push_back(field);
    }
    void print() const {
        for (const auto & field: fields) {
            field.print(); std:: cout << " ";
        }
    }
};
```

# Constructing Generalized Tuples

```
void BuzzDB::insert(int key, int value) {
  Tuple newTuple;
  Field key_field = Field(key);
  Field value_field = Field(value);
  float float_val = 132.04;
  Field float_field = Field(float_val);

  newTuple.addField(key_field);
  newTuple.addField(value_field);
  newTuple.addField(float_field);

  table.push_back(newTuple);
  index[key].push_back(value);
}
```

# Further Generalization to Strings

FieldType enum includes STRING

```
enum FieldType {INT, FLOAT, STRING}

class Field {
    public:
    FieldType type;
    union {
        int i;
        float f;
        char *s; // string
    } data;
    ...
}
```

# More Generalization to Strings

Polymorphic Container

Field Object

Floating Point

String Form

DATABASE = 8 Letters

POLYMORPHISM = 12 Letters

# More Generalization to Strings

## Dynamic Memory Allocation

String Parameter S

Field Object to String

String S + 1

Memory data.s

```
Field(const std::string &s) : type(STRING) {
  data.s = new char[s.size() + 1];
  std::copy(s.begin(), s.end(), data.s);
  data.s[s.size()] = '\0'; // Null-terminate the string
}
```

# New Operator


Dynamic Memory Allocation

Heap-Allocated Variable

Explicit Variable Destruction

```
data.s = new char[s.size() + 1];
```

# Destructors in C++


Field Class Destructor

Cleans Memory

Data.s ≠ nullptr

```
Field::~Field() {
  if (type == STRING && data.s != nullptr) {
    delete[] data.s;
  }
}
```

# Delete Operator


Heap Memory Clearance

Corresponding Delete Operator

Avoid System Crashes

```
delete ptr;   // Frees memory allocated for a single integer
delete[] arr; // Frees memory allocated for an array of integers
```

# Raw Pointers

# Raw Pointers

Field Class + Raw Character Pointer

```
enum FieldType {INT, FLOAT, STRING}

class Field {
    public:
    FieldType type;
    union {
        int i;
        float f;
        char *s;
    } data;
    ...
};
```

# Perils of Raw Pointers

## Four Important Problems

- Memory Leaks
- Dangling Pointers
- Double-free Errors
- Ownership Ambiguity

# Perils of Raw Pointers: Memory Leaks

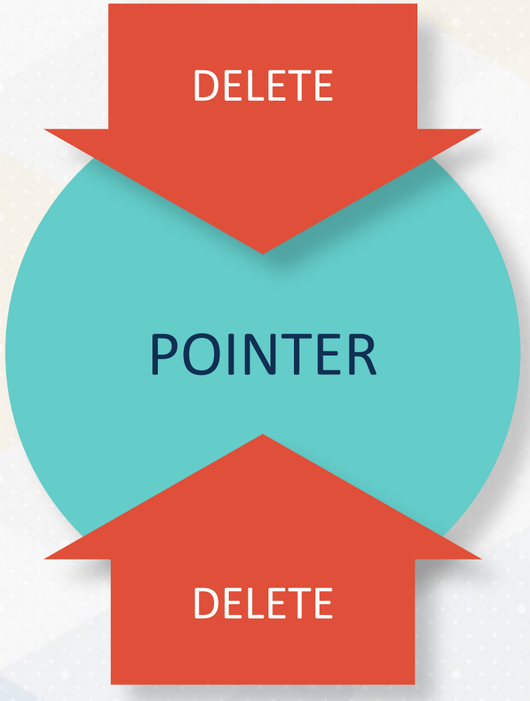
Explicit Deletion Required

```
void createMemoryLeak() {
  int *leakyPtr = new int(42); // Allocation
  // Forgot to delete leakyPtr
  // Memory allocated to leakyPtr is never freed
}
```

# Perils of Raw Pointers: Dangling Pointers


```
void createDanglingPointer() {
    int * danglyPtr = new int(42)
    delete danglyPtr
    // Deallocate memory
    // danglyPtr now becomes a dangling pointer
    std:: cout << *danglyPtr
    // Undefined behavior, potentially a crash
}
```

# Perils of Raw Pointers: Double-Free Errors




```
void createDoubleFree() {
  int *doubleTroublePtr = new int(42);
  delete doubleTroublePtr; // Correct deletion
  delete doubleTroublePtr; // Double free, leads to runtime error
}
```

# Perils of Raw Pointers

No Clear Ownership

Unclear Deallocation

Unclear Memory Management

```
int *function1(int *ptr) {
  // It's unclear if the function should delete ptr
  // Function logic here...
  return new int(55); // Should the caller delete the returned pointer?
}
void function2() {
  int *myPtr = new int(42);
  int *newPtr = function1(myPtr);
  // Who owns myPtr and newPtr? Who is responsible for deleting them?
}
```

# Smart Pointers

# Smart Pointers

- std::unique_ptr
- Code Safety
- Readability
- Maintainability

# Smart Pointers: Avoid Memory Leaks

```cpp
#include <memory>


void createMemoryLeak() {
  std::unique_ptr<int> safePtr =
      std::make_unique<int>(42); // Automatic management
                                 // No need to manually delete;
  // memory is automatically freed when safePtr goes out of scope
}
```

std::unique_ptr

Manages Memory

Scope Deallocation

# Smart Pointers: Avoid Dangling Pointers

After calling reset(), safePtr safely releases its ownership and avoids becoming a dangling pointer by setting itself to nullptr

```
void createDanglingPointer() {
  std::unique_ptr<int> safePtr = std::make_unique<int>(42);
  safePtr.reset(); // Correctly frees memory and sets pointer to nullptr
  // safePtr is now nullptr, preventing access to freed memory
}
```

# Smart Pointers: Avoid Doube-Free Errors

std::unique_ptr enforces unique ownership of the managed object, meaning that the memory is freed exactly once when the pointer goes out of scope or is reset.

Prevents double-free errors

```
void createDoubleFree() {
  std::unique_ptr<int> safePtr = std::make_unique<int>(42);
  // safePtr goes out of scope and automatically deletes the managed object
  // No risk of double free errors
  // as unique_ptr ensures single ownership and controlled deletion
}
```

# Smart Pointers: Avoid Ownership Ambiguity

unique_ptr clarifies ownership through its ownership model

```
std::unique_ptr<int> function1(std::unique_ptr<int> ptr) {
  // Ownership is clearly transferred with unique_ptr, no ambiguity
  return std::make_unique<int>(55);
  // Returning a new unique_ptr transfers ownership back to the caller
}
void function2() {
  std::unique_ptr<int> myPtr = std::make_unique<int>(42);
  std::unique_ptr<int> newPtr = function1(std::move(myPtr));
  // Ownership transfer is explicit with std::move,
  // clarifying lifecycle management
}
```

# Conclusion

- Storage management
- Generalized Tuple class
- Smart Pointers