CSE 1325: Object-Oriented Programming

Lecture 21

Concurrency and Hyperthreading
Deployment Diagrams
Decorator Pattern

Mr. George F. Rice

george.rice@uta.edu

Based on material by Bjarne Stroustrup

www.stroustrup.com/Programming

ERB 402

Office Hours:

Tuesday Thursday 11 - 12

Or by appointment

Quick Review

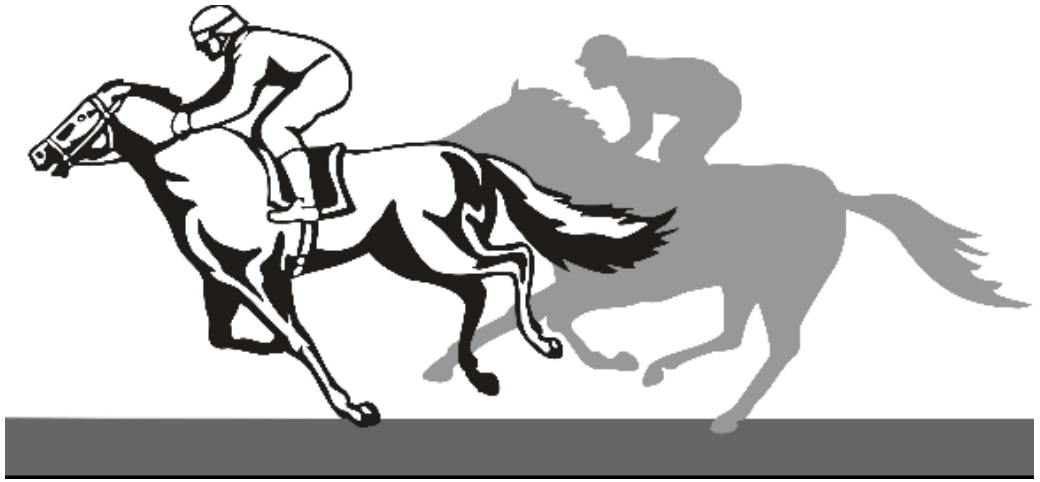
- **Stack** is “scratch memory for a thread. **Heap** (or **Free Store**) is memory shared by all threads for dynamic allocation.
- If new cannot allocate memory (for example, because there is not enough memory available), what does C++ do? **Throw a bad_alloc exception**
- Give 2 examples of errors that may cause a memory leak. **Failing to delete the heap via a pointer. Overwriting a pointer before deleting the heap to which it points.**
- Identify 3 strategies to avoid memory leaks. **Avoid new, using STL classes instead. Use smart pointers or Gtk::Manage. Allocate memory in constructors and deallocate in destructors.**
- **delete[ ]** de-allocates arrays from the heap, whicle **delete** de-allocates normal variables.
- The closest feature that C++ has to providing raw memory is the **void***.
- Select the phrase or phrases that best describe a reference. **All of them!**
  - An automatically dereferenced pointer
  - A constant pointer whose address can’t change
  - An alias for another object

Quick Review

- Writing algorithms in terms of types that are specified as parameters during instantiation or invocation is called **generic programming**.
- A **template** is a C++ construct representing a function or class in terms of generic types.
- **True** or False: Both the declaration AND definition of a template class must be placed in the header file.
- The Standard Template Library (STL) links algorithms to containers using **iterators**.
- **True** or False: With iterators, the end of the sequence is “one past the last element”, not “the last element”
- Two types of iterators are typically provided, **iterator** and **const iterator**.
- Name some common iterator and container methods in the STL.
  Iterator: operator=, operator++, operator--, operator*, operator==
  Container: begin, end, front, back, empty, push_back, pop_back, insert, erase
- True or **False**: It is a good practice to derive your classes from STL classes.

Overview: Concurrency, Adapter Pattern, & Deployment Diagrams

- Introduction to Concurrency
  - Brief history
  - Uses
  - C++ Support
    - Thread class
    - Sleep
    - Conflicts / Race
    - Mutex



- Adapter Pattern
- Deployment Diagrams

Concurrency and Hyperthreading

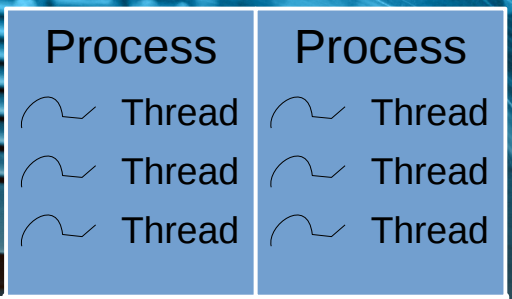
A Brief History of Concurrency

- **Moore's Law** (paraphrased): Computer tech (originally transistor density) doubles every 2 years
  - CPU speed, transistor and memory density, disk capacity, etc.
- By the 21st century, Moore's Law began to crack
  - Processor speeds topped out around 4 GHz (2.8 – 3.4 common)
  - Transistor density continued for some time – but how to best use?
- **Multi-Core Processor** – a chip with multiple **cores**, or ALU/register sets, each running a separate thread
  - Intel worked out use of one ALU with 2 register sets, interleaving 2 threads of execution – **Hyperthreading**
- Recently deployed 24 hyperthreaded core machines – but how to utilize so many cores?

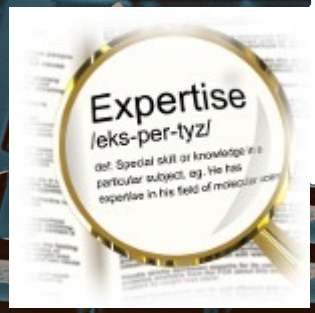
Concurrency

Concurrency

- “I do one thing, I do it very well, and then I move on” – Dr. Charles Emmerson Winchester III
- “Move on, Chaaarles” – Hawkeye
- **Concurrency** – Performing 2 or more algorithms (as it were) simultaneously
- **Process** – A self-contained execution environment including its own memory space.
- **Thread** – An independent path of execution within a process, running concurrently (as it appears) with other threads within a shared memory space.



Conceptual Model



https://gcc.gnu.org/wiki/cauldron2015?action=AttachFile&do=get&target=Torvald+Riegel_+Modern+concurrent+code+in+C.pdf

Good Uses for Concurrency

- Perform background processing independent of the user interface, e.g., communicating the game state to apps
- Programming logically independent program units, e.g., the behavior of each non-player character in a game
- Processing small, independent units of a large problem, e.g., calculating the shaded hue of each pixel in a rendered photograph – or rendering an entire movie frame by frame!
- Periodic updating of a display or hardware unit, e.g., updating the second hand of a clock
- Periodic collection of data, e.g., capturing wind speed from an anemometer every 15 seconds

Creating a C++ Thread via Thread

- Class std::thread represents a thread of execution
  - Each thread has a unique thread ID (.get_id())
  - Each initialized thread can be “joined” back to the main thread (a non-initialized thread can't)

```
#include <string>
#include <iostream>
#include <thread>
using namespace std;

// The function we want to execute on the new thread
void task1(string msg) {
    cout << "task1 says: " << msg << endl;
}

int main() {
    // Constructs the new thread and runs it. Does not block execution.
    thread t1(task1, "Hello");
    cout << "Thread 1 ID is " << t1.get_id() << endl;

    // Makes the main thread wait for the new thread to finish execution
    t1.join();
}
```

Creating a C++ Thread via Thread

- Class std::thread represents a thread of execution
  - Each thread has a unique thread ID (.get_id())
  - Each initialized thread can be “joined” back to the main thread (a non-initialized thread can't)

```
#include <string>
#include <iostream>
#include <thread>
using namespace std;

// The function we w
void task1(string ms
    cout << "task1 s
}

int main() {
    // Constructs the new thread and runs it. Does not block execution.
    thread t1(task1, "Hello");
    cout << "Thread 1 ID is " << t1.get_id() << endl;

    // Makes the main thread wait for the new thread to finish execution
    t1.join();
}
```

```
ricegf@pluto:~/dev/cpp/201608/threads$ g++ -std=c++11 threadid.cpp
ricegf@pluto:~/dev/cpp/201608/threads$ ./a.out
terminate called after throwing an instance of 'std::system_error'
  what():  Enable multithreading to use std::thread: Operation not permitted
Aborted (core dumped)
ricegf@pluto:~/dev/cpp/201608/threads$ g++ -std=c++11 -pthread threadid.cpp
ricegf@pluto:~/dev/cpp/201608/threads$ ./a.out
Thread 1 ID is 7f6211307700
task1 says: Hello
ricegf@pluto:~/dev/cpp/201608/threads$
```

Must compile with -pthread

C++ Offers a *Hint* at HW Support

- thread:hardware_concurrency() returns a rough estimate of the number of *concurrent* threads
  - This may represent cores or hyperthreaded half-cores
  - This may return 0 or nothing relevant at all

```
#include <string>
#include <iostream>
#include <thread>

using namespace std;

int main()
{
    // Show rough approximation of thread capacity
    cout << "Hardware concurrency is " << thread::hardware_concurrency() << endl;
}
```

```
ricegf@pluto:~/dev/cpp/201608/threads$ g++ -std=c++11 -pthread hw_concurrency.cpp
ricegf@pluto:~/dev/cpp/201608/threads$ ./a.out
Hardware concurrency is 4
task1 says: Hello
ricegf@pluto:~/dev/cpp/201608/threads$
```

Threads can be Confusing

- Both main() and t1() execute independently
  - Threads can switch execution *between microprocessor instructions* (not C++ lines) at any time
  - This can garble output

Ungarbled output

```
ricegf@pluto:~/dev/cpp/threads$ g++ -std=c++0x -pthread threadid.cpp
ricegf@pluto:~/dev/cpp/threads$ ./a.out
Thread 1 ID is 140301458634496
task1 says: Hello
ricegf@pluto:~/dev/cpp/threads$
```

Garbled output

```
ricegf@pluto:~/dev/cpp/threads$ ./a.out
Thread 1 ID is 1404682637125 12task1 says:
Hello
ricegf@pluto:~/dev/cpp/threads$
```

  - We'll see how to avoid this in a bit

Sleeping a Thread

- It's tempting to pause a thread using a “busy loop”

```
for (int i = 0; i < 100000; ++i) { } // Wait a while
```

- This is *very* problematic
  - Compilers are very smart nowadays, and may optimize away the useless loop
  - Processor speeds vary widely, so timing is uncertain
  - If it runs the instructions, it's burning valuable CPU cycles that could be used by other threads
- Instead, use this_thread::sleep_for

```
this_thread::sleep_for(chrono::milliseconds(2000); // or seconds(2)
```

Sleeping 3 Threads Randomly

```
#include <string>
#include <iostream>
#include <thread>
#include <chrono>
#include <time.h>
using namespace std;

void task1(string msg) {
    this_thread::sleep_for(chrono::milliseconds(200+rand()%200));
    cout << "task1 says: " << msg << endl;
}

int main() {
    // Randomize the pseudorandom number generator
    srand(time(NULL));

    // Construct new threads
    thread t1(task1, "Hello");
    thread t2(task1, "Bonjour");
    thread t3(task1, "Hola");

    // Join all threads back
    t1.join();
    t2.join();
    t3.join();
}
```

Sleeping 3 Threads Randomly

```
#include <string>
#include <iostream>
#include <thread>
#include <chrono>
#include <time.h>
using namespace std;

void task1(string msg) {
    this_thread::sleep_for(chrono::milliseconds(200+rand()%200));
    cout << "task1 says: " << msg << endl;
}

int main() {
    // Randomize the pseudorandom number generator
    srand(time(NULL));

    // Construct new threads
    thread t1(task1, "Hello"
    thread t2(task1, "Bonjou
    thread t3(task1, "Hola")

    // Join all threads back
    t1.join();
    t2.join();
    t3.join();
}
```

```
ricegf@pluto:~/dev/cpp/201608/threads$ g++ -std=c++11 -pthread 3thread.cpp
ricegf@pluto:~/dev/cpp/201608/threads$ ./a.out
task1 says: Bonjour
task1 says: Hola
task1 says: Hello
ricegf@pluto:~/dev/cpp/201608/threads$ ./a.out
task1 says: Hello
task1 says: Hola
task1 says: Bonjour
ricegf@pluto:~/dev/cpp/201608/threads$ ./a.out
task1 says: Hola
task1 says: Hello
task1 says: Bonjour
ricegf@pluto:~/dev/cpp/201608/threads$
```

Tasks may start and run *in any order*

Applying Threads to Serious Work (Race Horses)

horse.h

```
#include <string>

using namespace std;

class Horse {
    public:
        Horse(string name, int speed)
      : _name{name}, _speed{speed}, _position{30} { }
        string name();
        int position();
        int speed();
        int move();
    protected:
        string _name;
        int _position;
        int _speed;
};
```

horse.cpp

```
#include "horse.h"

using namespace std;

string Horse::name() {return _name;}
int Horse::position() {return _position;}
int Horse::speed() {return _speed;}
int Horse::move() {if (_position > 0) --_position;}
```

Utility functions

horserace.cpp

```
#include <string>
#include <iostream>
#include <thread>
#include <chrono>
#include <time.h>
#include "horse.h"

using namespace std;

// Our three competitors, assigned random speeds (smaller is faster)
Horse horse1("Legs of Spaghetti", 100 + rand() % 100);
Horse horse2("Ride Like the Calm", 100 + rand() % 100);
Horse horse3("Duct-taped Lightning", 100 + rand() % 100);

// The gallop threads, which decrement position after a random delay
void gallop(Horse& horse) {
    while (horse.position() > 0) {
        this_thread::sleep_for(
            chrono::milliseconds(horse.speed() + rand() % 200));
        horse.move();
    }
}

// Utility function to print the horse track
void view(int position) {
    for (int i = 0; i < position; ++i) cout << (i%5 == 0 ? ':' : '.');
}                                          // Continued next page
```

main()

horserace.cpp

```
int main() {
    // Randomize the pseudorandom number generator
    srand(time(NULL));

    // Construct the new threads (horses) and run them
    thread t1{gallop, ref(horse1)};
    thread t2{gallop, ref(horse2)};  // ref( forces the parameter to pass as
    thread t3{gallop, ref(horse3)};  // a reference rather than a value

    // Display the horse track as the race runs
    while (horse1.position() > 0
       &&  horse2.position() > 0
       &&  horse3.position() > 0) {
        cout << endl << endl << endl << endl;
        view(horse1.position());
        cout << " " << horse1.name() << endl;
        view(horse2.position());
        cout << " " << horse2.name() << endl;
        view(horse3.position());
        cout << " " << horse3.name() << endl;
        this_thread::sleep_for(chrono::milliseconds(100));
    }

    // Join the threads
    t1.join();
    t2.join();
    t3.join();
}
```

The Obligatory Makefile

Makefile

```
CXXFLAGS += -std=c++11 -pthread

all: main

debug: CXXFLAGS += -g
debug: main

rebuild: clean main

main: horserace.o horse.o
        g++ -o horserace $(CXXFLAGS) horserace.o horse.o
horserace.o: horserace.cpp horse.h
        g++ $(CXXFLAGS) -c horserace.cpp
horse.o: horse.cpp horse.h
        g++ $(CXXFLAGS) -c horse.cpp
clean:
        -rm -f *.o *~ horserace
```

:.. Ride Like the Calm
:.... Duct-taped Lightning

:....: Legs of Spaghetti
:.. Ride Like the Calm
:.... Duct-taped Lightning

:....: Legs of Spaghetti
:.. Ride Like the Calm
:... Duct-taped Lightning

:.... Legs of Spaghetti
:.. Ride Like the Calm
:... Duct-taped Lightning

:.... Legs of Spaghetti
:. Ride Like the Calm
:... Duct-taped Lightning

:.... Legs of Spaghetti
:. Ride Like the Calm
:.. Duct-taped Lightning

:.... Legs of Spaghetti
: Ride Like the Calm
:.. Duct-taped Lightning

Running the Race

(It's a lot easier to follow live!)

Concurrency is Harder than Single-Threaded

- Non-reentrant code can lose data
  - **Reentrant** – An algorithm can be paused while executing, and then safely executed by a different thread
  - Non-reentrant code can experience **Thread Interference**
- Methods that aren't **thread safe** enable Threads to corrupt objects
  - Thread A updates a portion of the object's data, while Thread B updates a dependent portion, leaving the object in an inconsistent state – the bug's impact occurs much later!
- Memory Consistency Errors
  - Because variables may be cached, one thread's change may never be incorporated by a different thread's algorithm
- Concurrent bugs tend to appear only when multiple threads happen to align, thus appearing to be both rare and random
  - Nightmare debugging scenario

The "Garbled Output" Problem Revisited

- Here's a (Java) example of a thread sync problem

(`javap -c Counter.class` disassembles bytecode)

```
public class Counter {
    private int count = 0;

    public void increment() {
        count++;
    }

    public void decrement() {
        count--;
    }

    public int getCount() {
        return count;
    }
}
```

```
public void increment();
  Code:
     0: aload_0
     1: dup
     2: getfield      #2
          // Field count:I
     5: iconst_1
     6: iadd
     7: putfield      #2
          // Field count:I
    10: return
```

Thread A

Paused here!

```
public void decrement();
  Code:
     0: aload_0
     1: dup
     2: getfield      #2
          // Field count:I
     5: iconst_1
     6: isub
     7: putfield      #2
          // Field count:I
    10: return
```

Thread B runs decrement

Thread A resumes

The change made by decrement in Thread B is overwritten by the obsolete data in Thread A. $+1-1 \stackrel{?}{=} 1$

Hint: Immutable Classes!

- If the data can't change, synchronization issues can't crop up *in that class*
  - Create and use immutable classes when practical
  - In an immutable class, mark all data fields as const to indicate those fields won't change
  - This isn't always possible...
  -

General C++ Solution: The Mutex

- Assume a crowd of people want to use an old-fashioned phone booth. The first to grab the door handle gets to use it first, but must hang on to the handle to keep the others out. When finished, the person exits the booth and releases the door handle. The next person to grab the door handle gets to use the phone booth next.

- A **thread** is: Each person
  The **mutex** is: The door handle
  The **lock** is: The person's hand
  The **resource** is: The phone

Hat tip to Nav on Stack Overflow for this analogy

The Mutex in Code

```
#include <iostream>
#include <thread>
#include <mutex>
using namespace std

mutex m;
int i = 0;

void makeACallFromPhoneBooth() {
    m.lock(); // person grabs the phone booth door and locks it, all others wait
    cout << i << " talks on phone" << endl;
    i++; //no other thread can access variable i until m.unlock() is called
    m.unlock(); // person releases the door handle and unlocks the door
}

int main() {
    thread person1(makeACallFromPhoneBooth); // Despite appearances, as we saw
    thread person2(makeACallFromPhoneBooth); // earlier, it is not clear who will
    thread person3(makeACallFromPhoneBooth); // reach the phone booth first!

    person1.join(); // person1 finished their phone call and joins the crowd
    person2.join(); // person2 finished their phone call and joins the crowd
    person3.join(); // person3 finished their phone call and joins the crowd
}
```

```
ricegf@pluto:~/dev/cpp/201608/threads$ g++ -std=c++11 -pthread phone.cpp
ricegf@pluto:~/dev/cpp/201608/threads$ ./a.out
0 talks on phone
1 talks on phone
2 talks on phone
ricegf@pluto:~/dev/cpp/201608/threads$
```

Testing the Mutex

```
#include <iostream>
#include <thread>
#include <mutex>
using namespace std;

static const int num_threads = 10;
static const int num_decrements = 500;

int counter = num_threads * num_decrements;

mutex m;

// This is the code to be run as threads
void decrementer() {
    for (int i=num_decrements; i > 0; --i) {
        m.lock(); --counter; m.unlock();
    }
}
int main() {
    //Launch a group of threads
    thread t[num_threads];
    for (int i = 0; i < num_threads; ++i) t[i] = thread(decrementer);

    //Join the threads with the main thread
    for (int i = 0; i < num_threads; ++i) t[i].join();

    cout << "This should be 0: " << counter << endl;
    return counter;
}
```

```
ricegf@pluto:~/dev/cpp/201608/threads$ g++ -std=c++11 -pthread mutex.cpp
ricegf@pluto:~/dev/cpp/201608/threads$ ./a.out
This should be 0: 0
ricegf@pluto:~/dev/cpp/201608/threads$
```

Allow 5000 chances for thread interference

Warning

- This just scratches the surface of concurrency
  - Avoiding race conditions is exceptionally tricky
  - Other dangers lurk, e.g., priority inversion
  - Bugs in concurrent systems are often catastrophic, but appear only once in a blue moon
- This lecture gives you just enough knowledge to get in trouble... or to motivate you to learn much more about a field growing in importance
  - Your decision...

Structural

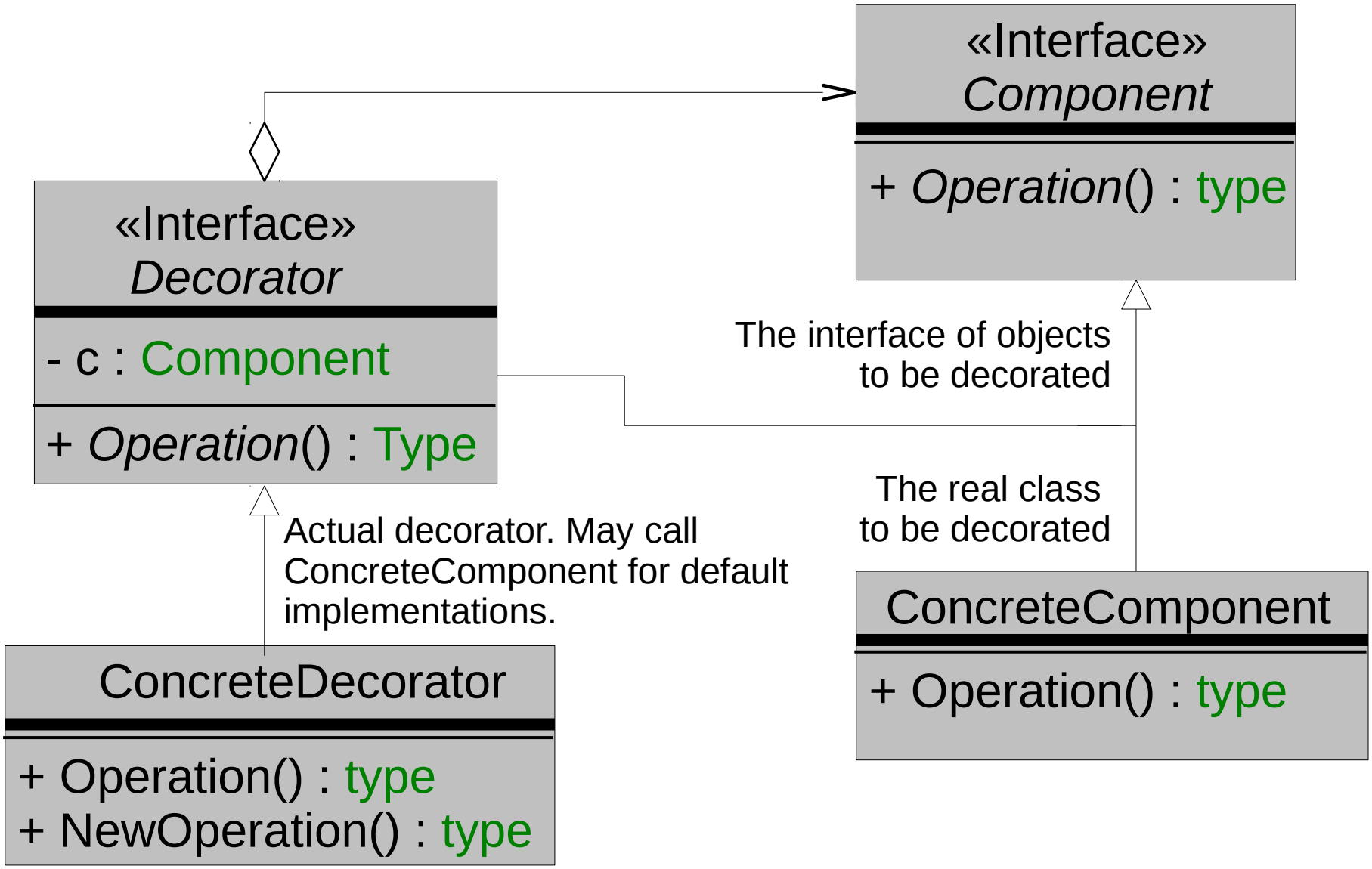
Decorator Pattern

- The **Decorator** pattern *dynamically* adds new functionality to an object without altering its structure
  - Distinct from inheritance, which is a *static* functionality addition
  - Decorator relies on composition to reuse the decorated class code, while adding additional code
  - Decorators are typically small, and overuse can impact supportability due to too many small similar classes

Structural

The Decorator Pattern

(Slightly Simplified)

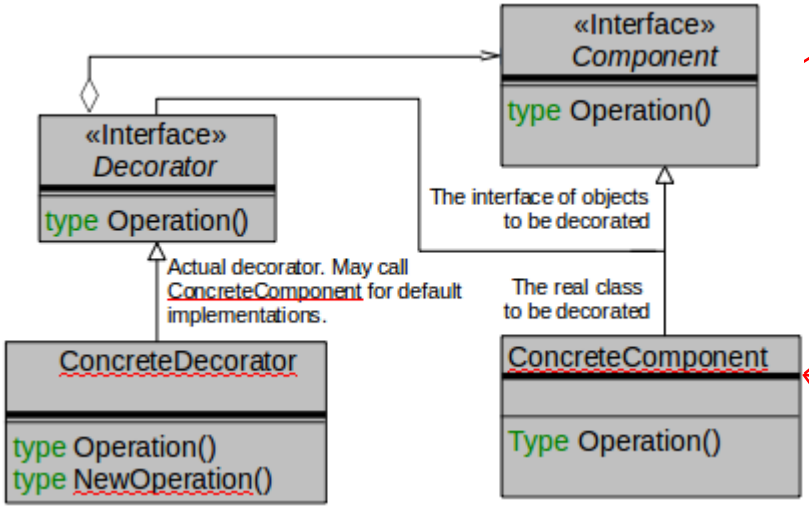


Structural

The Decorator Pattern

(Slightly Simplified)

Classes to be decorated




```
// The component interface
class Robot {
  public:
    void announce();
};

// The concrete product classes
class WalkingRobot : public Robot {
  public:
    void announce()
        cout << “Make way!” << endl;
};

class FlyingRobot : public Robot {
  public:
    void announce()
        cout << “Heads up!” << endl;
};

class DivingRobot : public Robot {
  public:
    void announce()
        cout << “Glub! Glub!” << endl;
};
```

Structural

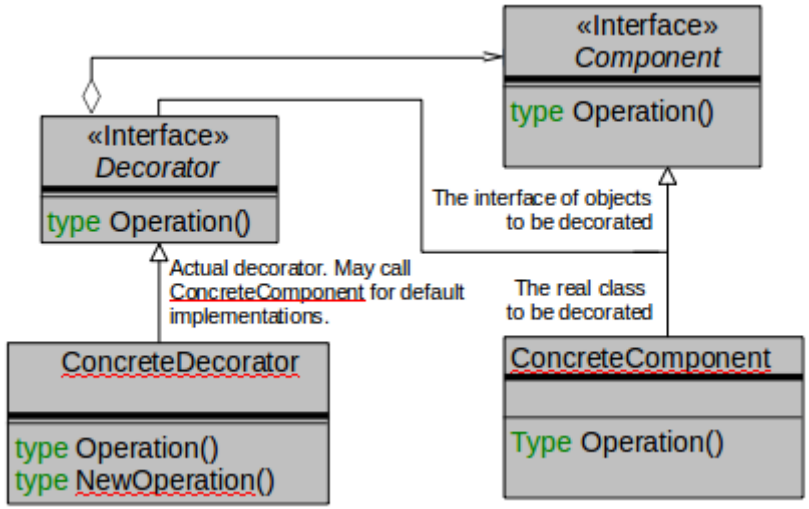
The Decorator Pattern

(Slightly Simplified)

Decorations

```
// The decorator interface or abstract class
class RobotDecorator : public Robot {
  protected:
    Robot _decoratedRobot;
  public:
    RobotDecorator(Robot decoratedRobot)
      :  _decoratedRobot{decoratedRobot} { }
    void announce()
        _decoratedRobot.announce();
};

// The concrete decorator class
class BeepRobotDecorator : public RobotDecorator {
  public:
    BeepRobotDecorator(Robot decoratedRobot)
      :  RobotDecorator(decoratedRobot) { };
    void announce() override {
        decoratedRobot.announce();
        cout << “Beep! Beep!” << endl;
    }
};
```

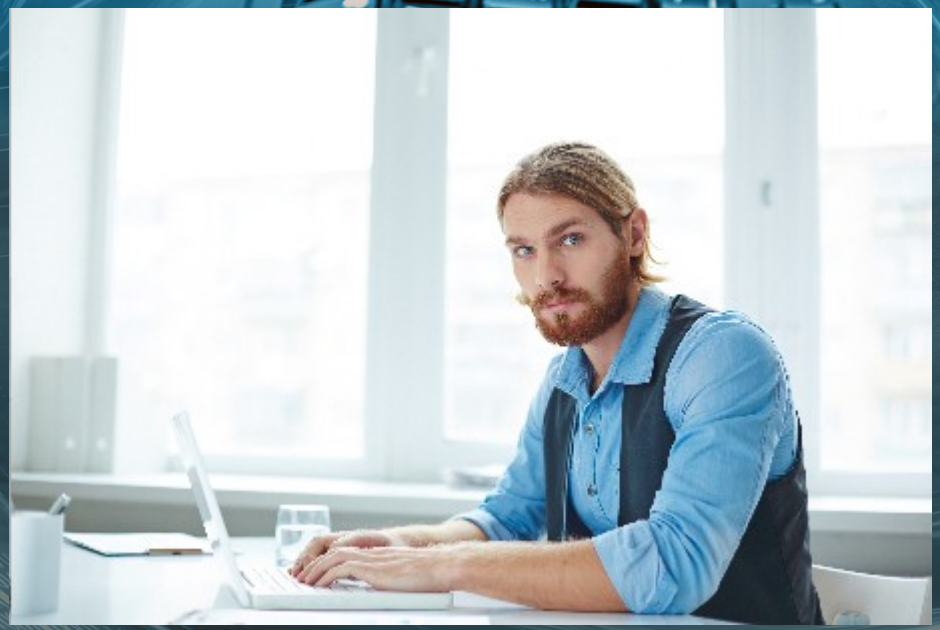


Applying Patterns

- Our Digital Signal Processing (DSP) application is designed to receive and process data from a QC-107 quadcopter drone.
- However, we could only afford the QC-53½ quadcopter drone, which has a different interface library not supported by our DSP application.
- This problem is a good candidate for the _____ pattern.

Applying Patterns

- Our company is expanding to 10 different sites around the world, each with its own local computing resources.
- When an employee seeks to launch an instance of a tool, we want to ensure that the instance is on computing resources local to that employee.
- This problem is a good candidate for the _____ pattern.



Applying Patterns

- Your team is developing a next-generation big data analysis tool that will revolutionize your industry, crush your competition, and possibly result in a pay raise.
- However, the tool's algorithms are dependent on the Goggles data reduction library, which is complex and difficult to learn and use. Only one team member has experience with this library.

- The tool needs only a small subset of the Goggles library functionality.
- This problem is a good candidate for the _____ pattern.

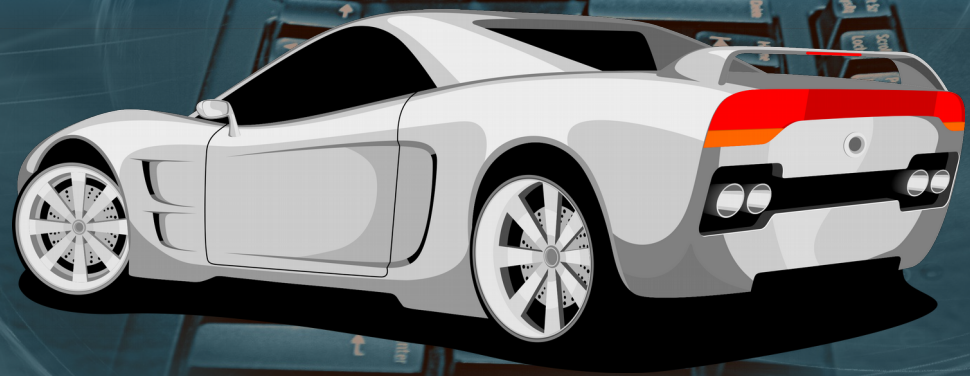
Applying Patterns

- After 42 sprints, your team is ready to deploy your new iPhone app to your eager worldwide fan base.

- To ensure your fan base doesn't become your plaintiffs, you want to collect data about app crashes and operational problems so you can proactively address any issues. One approach is for your data collection server to register to be notified when an installed app detects any anomalies.
- This problem is a good candidate for the _____ pattern.

Applying Patterns

- Your new self-driving car software will dominate the coming auto-Uber market by steering each wheel *individually* for optimal maneuvering.
- A central controller program determines the optimal angle of each wheel. However, it's rather important that only one central controller coordinate all 4 wheels, otherwise Bad Things might happen.
- This problem is a good candidate for the _____ pattern.



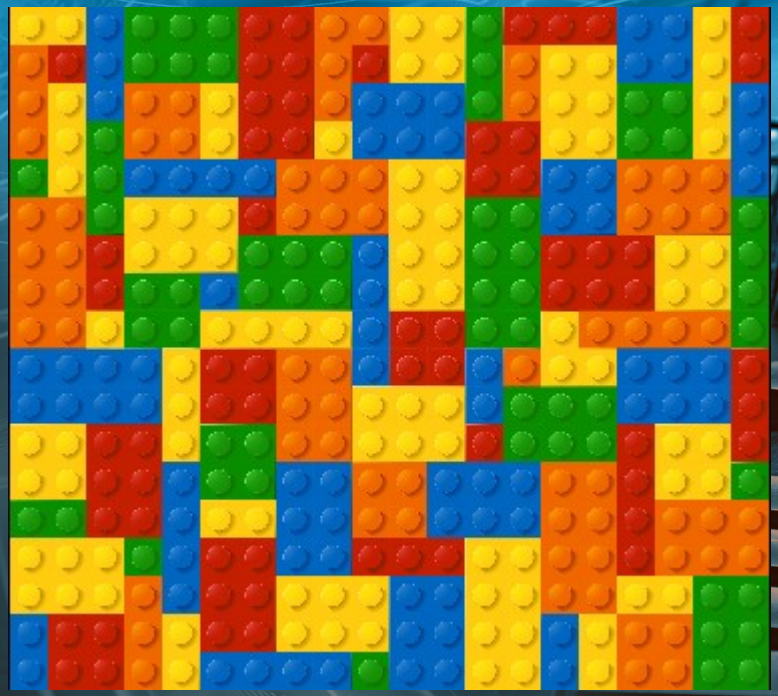
Applying Patterns

- Your Internet of Things (IoT) application will build an ad hoc network out of the outlets in a building. Your product backlog specifies that your application must try to establish the network via wifi, bluetooth, power line net, infrared, and audio comm technologies, and then use the one that works best in that specific building.
- This problem is a good candidate for the _____ pattern.

Applying Patterns

- Which pattern(s) weren't covered?
- Give an example scenario where each would be appropriate to resolve design issues.

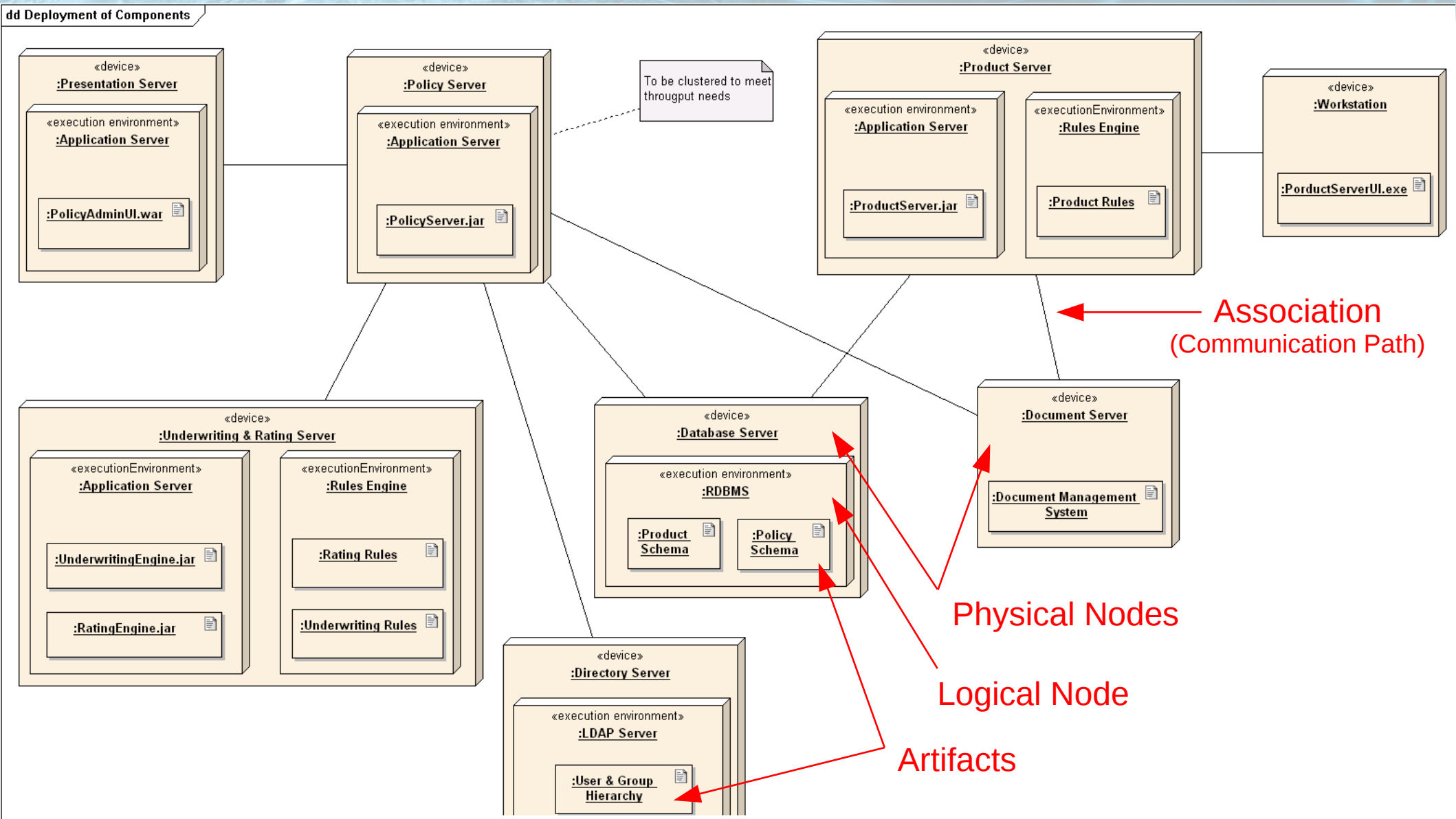
Deployment Diagrams



UML Deployment Diagrams

- A Deployment Diagram models the physical deployment of **artifacts** on **nodes**.
  - An **artifact** is the result of the software development process, e.g., an executable file, media file, script, database table, office document, or archive file.
    - An artifact may be defined recursively, e.g., an archive file that contains executables, resources, and installer.
  - A **node** is a physical or logical computational resource
    - A physical node (**device**) is a computer, and may be recursively defined (e.g., x64 processors consisting of multiple cores each)
    - A logical node (**execution environment**) is software that supports the asset, e.g., an operating system, virtual machine, or cloud server cluster

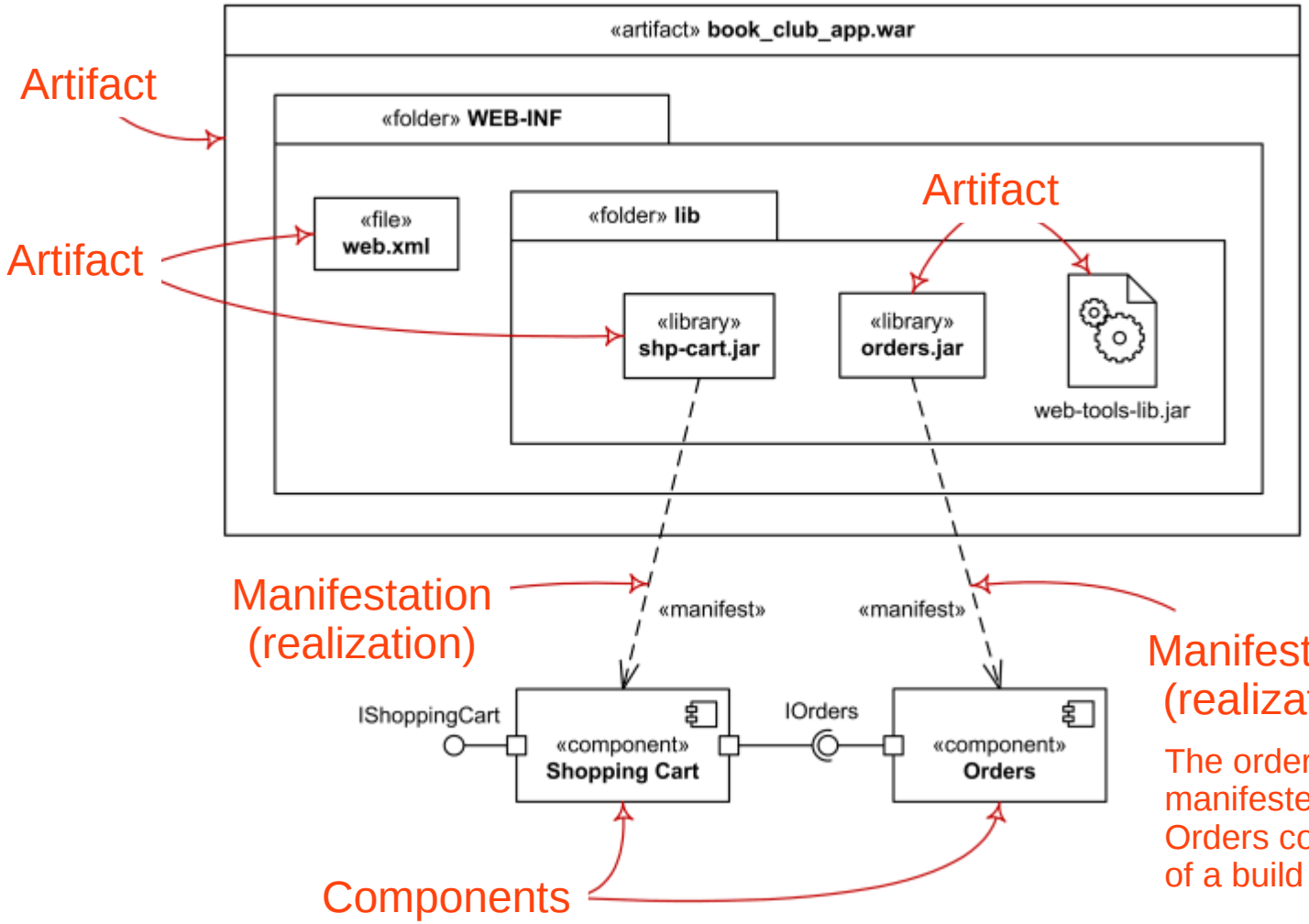
Example Deployment Diagram



4 Types of Deployment Diagrams

- Implementation of Components by Artifacts
  - Shows the manifestation (realization) of components (the result of the build) into artifacts (the configuration of components that can be deployed)
  - May also model the nested folder structure inside an artifact
- Specification-Level Deployment
  - Overview of deployment by artifact and node *types* (i.e., classes), without reference to specific instances
  - Often used to describe workstation or virtual server configurations
- Instance-Level Deployment
  - Shows deployment of specific *instances* (i.e., objects) of artifacts, e.g., by file name, to specific nodes, e.g., by server name
- Network Architecture
  - Represents connection of nodes via communication paths
  - Often the nodes are stereotyped and represented by more meaningful icons than the UML standard “3D cube” icon

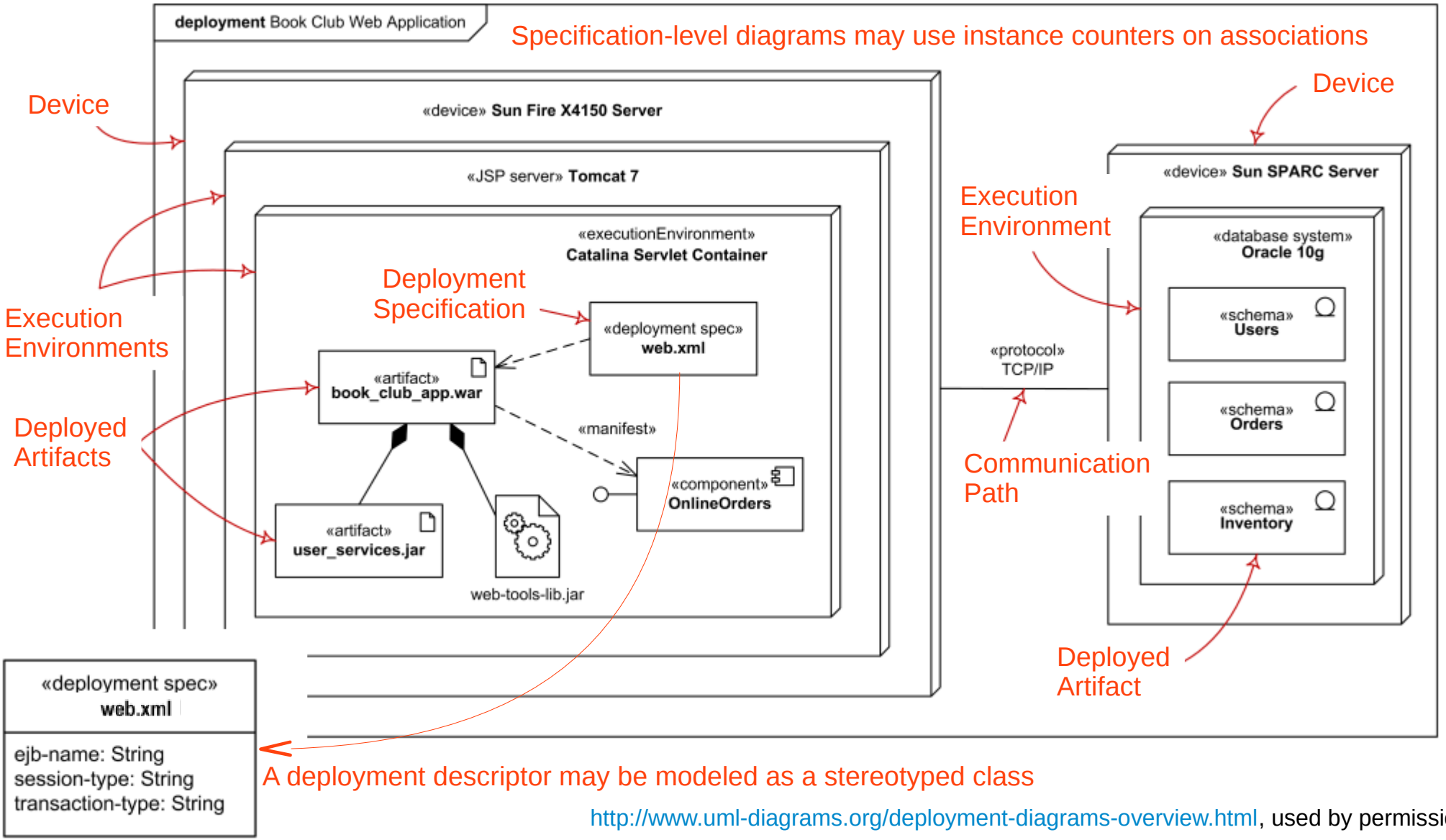
Manifestation of Components by Artifacts



The orders.jar artifact is manifested (built) from the Orders component (the result of a build process)

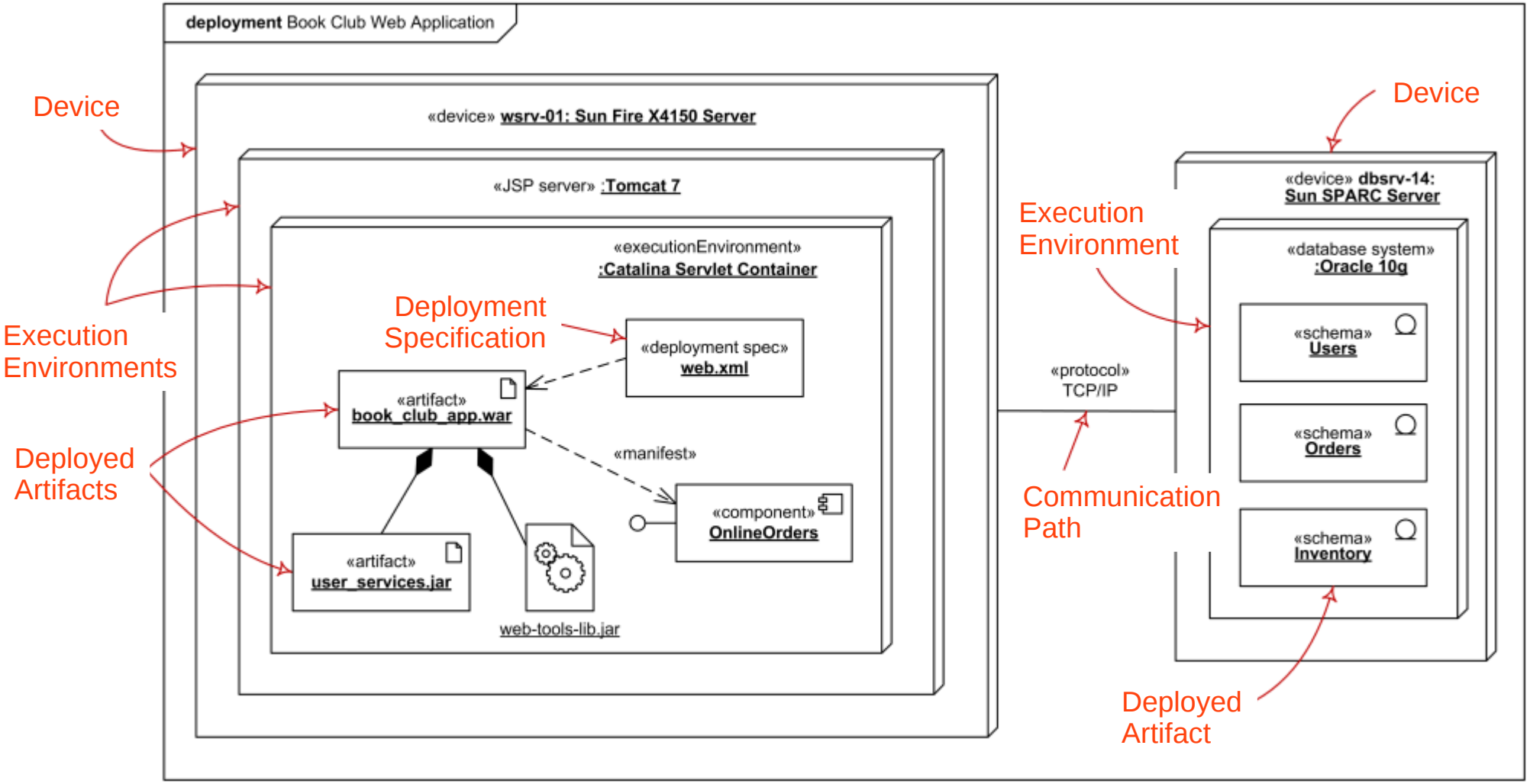
http://www.uml-diagrams.org/deployment-diagrams-overview.html, used by permission

Specification-Level Deployment



http://www.uml-diagrams.org/deployment-diagrams-overview.html, used by permission

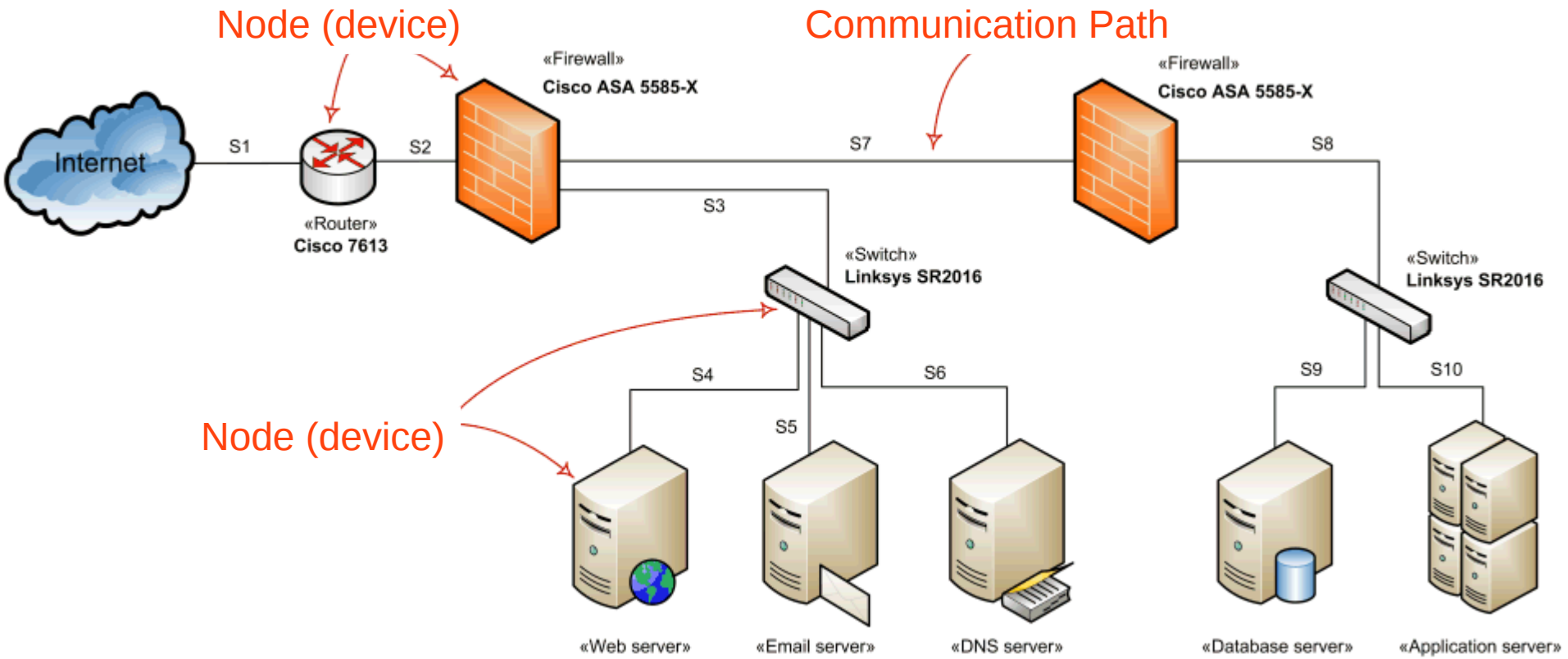
Instance-Level Deployment



Note the ":" and specific server names indicating instances rather than classes

http://www.uml-diagrams.org/deployment-diagrams-overview.html, used by permission

Network Architecture



Note the custom iconography for the nodes, providing a richer visual representation of the network

http://www.uml-diagrams.org/network-architecture-diagrams.html, used by permission

Quick Review

- _____ is one ALU/register set on a CPU, which runs one thread at a time. _____ is when one ALU has 2 register sets, interleaving 2 threads.
- Match the definition to either process, thread, or concurrency.
  - Performing 2 or more algorithms (as it were) simultaneously
  - A self-contained execution environment including its own memory space
  - An independent path of execution within a process, running concurrently (as it appears) with other threads within a shared memory space.
- List 3 problems with busy loops. What's the better alternative?
- What does joining a thread accomplish?
- Describe the “garbled output” (sync) problem. How do invariant classes help? How does a mutex solve the problem for the general case?

Quick Review

- The _____ _____ creates new objects without exposing the creation logic to the client. List some capabilities and advantages of this pattern and situations where it may apply.
- A _____ _____ models the physical deployment of artifacts on nodes.
  - An _____ is the result of the software development process
  - A ____ is a physical or logical computational resource
  - A physical node (device) is typically a _____. Give an example.
  - A logical node (execution environment) is _____ that supports the asset. Give an example.
- Which of the follow are deployment diagram types?
  (A) Network Architecture (B) Military (C) .cpp and .h
  (D) Manifestation of Artifacts by Components (E) EXE
  (F) Specification-Level Deployment (G) Instance-Level Deployment
- The _____ _____ dynamically adds new functionality to an object without altering its structure

For Next Thursday

Tuesday is Project Day – no class, extended office hours

- (Optional) Read Chapters 20-21 in Stroustrop
  - Do the Drills!
- Skim Chapters 23-24 for next week
- **Sprint #4 now in progress: Save the Data!**
  - **Individuals**: Maintain a cash register with persistent data (save and load), and manage order state!
  - **Duos:** It's reports week! And ice cream photos, too!
  - **Trios:** Restock and edit items and salaries, plus more reports!
  - **Quattros:** Support the franchises! Edit and retire items!