Project 1: Buffer Manager

Due on Wednesday 04/22/21 by 11:59PM PT

INTRODUCTION

The goal of the BadgerDB projects is to give you a hands-on education about two key components of an RDBMS. In this project, you are required to implement a buffer manager on top of a storage manager that is provided.

Logistics

BadgerDB is coded in C++. Here are a few logistical points:

- **Platform:** Your code will be compiled and tested on an AWS EC2 instance that runs an image which we will provide to you. We will use the g++ compiler (version 7.5.0) on these machines. You are free to develop your code on other platforms. We recommend using Linux with basic tools like git, make and g++ installed but **you must make sure that your code compiles and runs without hitches on an AWS EC2 instance running the image we provide**. You would be provided with AWS credits worth $50 for running your instances. The instructions to setup the EC2 instance are at the end of this document. If you are unable to setup an EC2 instance either due to the lack of an account or some other technical glitch, please email the TA and the instructor.

- **Warnings:** One of the strengths of C++ is that it does compile time code checking (consequently reducing run-time errors). Try to take advantage of this by turning on as many compiler warnings as possible. The Makefile that we will supply will have `-Wall` on as default.

- **Auxiliary Tools :** Always be on the lookout for tools that might simplify your job. Example: make for compiling and building your project, *makedepend* for automatically generating dependencies, *perl* or *python* or *bash* for writing test scripts, *valgrind* for tracking down memory errors, *gdb* for debugging, and *cvs* for version control. While we will not explicitly educate you about these tools, feel free to seek the TA's advice or post your questions on the class Piazza page.

- **Software Engineering:** A large project such as this requires significant software design effort. Spend some time thinking about your overall approach before you start writing any code.

Evaluation

We will run a bunch of our own (private) tests to check your code. So please develop tests beyond the ones that we give you to stress test your solution. We will also browse your code to review your coding style and read your Doxygen-generated files. 80% of each project grade is allocated to the correctness tests, and 20% for your coding style and clarity of documenting your code.

Academic Integrity

You are **not allowed to share any code** with other students in the class. Do not attempt to use any code from previous offerings of this course either. Do not attempt to source code from other people online or elsewhere; you are expected to write your code yourself and know how it works in detail. We will use code diffing programs and other program analysis tools to find cheaters. We might also conduct in-person code interviews of students suspected to have shared code or obtained code through dubious means. Students found engaging in the such malpractices **will be reported to the University authorities** for disciplinary action to be taken.

THE BADGERDB I/O LAYER

The lowest layer of the BadgerDB database system is the I/O layer. This layer allows the upper level of the system to create/destroy files, allocate/deallocate pages within a file, and to read/write pages of a file. This layer consists of two classes: a file (class File) and a page (class Page) class. These classes use C++ exceptions to handle the occurrence of any unexpected event. The implementations of the File class, the Page class, and the exception classes are provided to you. To start this project, you can download the zipped folder to your private workspace from `http://cseweb.ucsd.edu/classes/sp21/cse132C-a/downloads/BufMgr.zip`. Then, decompress the folder using the following command: `unzip BugMgr.zip`.

The code has been adequately commented to help you with understanding how it does what it does. Please use *Doxygen* as shown below to generate documentation for your code. Inside the **bufmgr** directory, run the following command to generate documentation files: `> make doc`. The doc files will be generated in docs directory. You can now open the `docs/index.html` file inside the browser and go through description of classes and their methods to better understand their implementation. Note that in the above, > is the shell prompt on Linux machines and not a part of the command.

THE BADGERDB BUFFER MANAGER

A database buffer pool is an array of fixed-sized memory buffers called frames that are used to hold database pages (also called disk blocks) that have been read from disk

into memory. A page is the unit of transfer between the disk and the buffer pool residing in main memory. Most modern DBMSs use a page size of at least 8,192 bytes. Another important thing to note is that a database page in memory is an exact copy of the corresponding page on disk when it is first read in. Once a page has been read from disk to the buffer pool, the DBMS software can update information stored on the page, causing the copy in the buffer pool to become different from the copy on disk. Such pages are termed *dirty*.

Since the database on disk itself is often larger than the amount of main memory that is available for the buffer pool, only a subset of the database pages may fit in memory at any given time. The buffer manager is used to control which pages are resident in memory. Whenever the buffer manager receives a request for a data page, the buffer manager checks to see if the requested page is already in the one of the frames that constitutes the buffer pool. If so, the buffer manager simply returns a pointer to the page. If not, the buffer manager frees a frame (possibly by writing to disk the page it contains, if the page is dirty) and then reads in the requested page from disk into the frame that has been freed.

Before reading further you should first read the documentation that describes the I/O layer of BadgerDB so that you understand its capabilities (described in the previous section). In a nutshell, the I/O layer provides an object-oriented interface to the Unix file with methods to open/close files and to read/write pages of a file. For now, the key thing you need to know is that opening a file (by passing in a character string name) returns an object of type *File*. This class has methods to read and write pages of the File. You will use these methods to move pages between the disk and the buffer pool.

Buffer Replacement Policies and the Clock Algorithm.

There are many ways of deciding which page to replace when a free frame is needed. Commonly used policies in operating systems are FIFO, MRU and LRU. Even though LRU is one of the most commonly used policies it has high overhead and is not the best strategy to use in a number of common cases that occur in database systems. Instead, many systems use the *clock algorithm* that approximates LRU behavior and is much faster.

Figure 1 shows the conceptual layout of a buffer pool. Figure 2 illustrates the execution of the clock algorithm.

In Figure 1, each square box corresponds to a frame in the buffer pool. Assume that the buffer pool contains *numBufs* frames, numbered 0 to numBufs-1. Conceptually, all the frames in the buffer pool are arranged in a circular list. Associated with each frame is a bit termed the *refbit*. Each time a page in the buffer pool is accessed (via a readPage() call to the buffer manager) the refbit of the corresponding frame is set to true. At any point in time the clock hand (an integer whose value is between 0 and numBufs - 1) is advanced (using modular arithmetic so that it does not go past numBufs - 1) in a clockwise fashion. For each frame that the clockhand goes past, the refbit is examined and then cleared. If the bit had been set, the corresponding frame has been referenced "recently" and is not replaced. On the other hand, if the refbit is false, the page is selected for replacement (assuming it is not pinned - pinned pages are discussed below). If the selected buffer frame

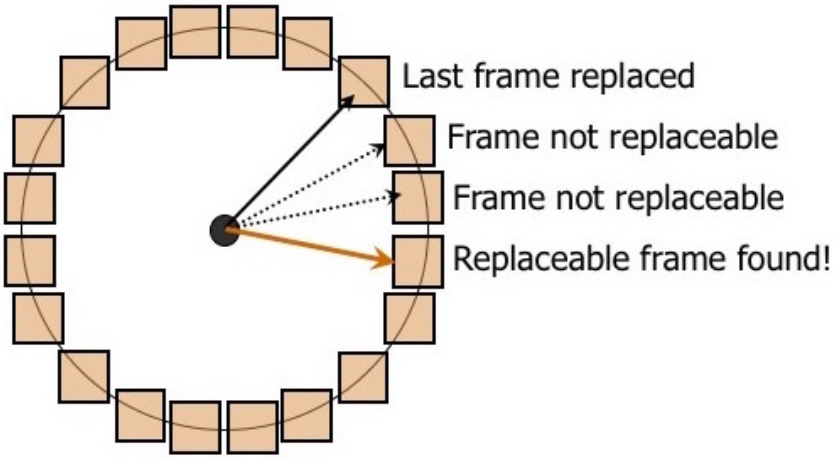


Figure 1: Structure of the Buffer Manager

is dirty (ie. it has been modified), the page currently occupying the frame is written back to disk. Otherwise the frame is just cleared and a new page from disk is read in to that location. The details of the algorithm is given below.

The Structure of the Buffer Manager.

The BadgerDB buffer manager uses three C++ classes: BufMgr, BufDesc and BufHashTbl. There is only one instance of the BufMgr class. A key component of this class is the actual buffer pool which consists of an array of numBufs frames, each the size of a database page. In addition to this array, the BufMgr instance also contains an array of numBufs instances of the BufDesc class that is used to describe the state of each frame in the buffer pool. A hash table is used to keep track of the pages that are currently resident in the buffer pool. This hash table is implemented by an instance of the BufHashTbl class. This instance is a private data member of the BufMgr class. These classes are described in detail below.

The BufHashTbl Class. The BufHashTbl class is used to map file and page numbers to buffer pool frames and is implemented using chained bucket hashing. We have provided an implementation of this class for your use.

```
struct hashBucket {
    File* file;      // pointer to a file object (more on this below)
    PageId pageNo;   // page number within a file
    FrameId frameNo;  // frame number of page in the buffer pool
    hashBucket* next;    // next bucket in the chain
};
```

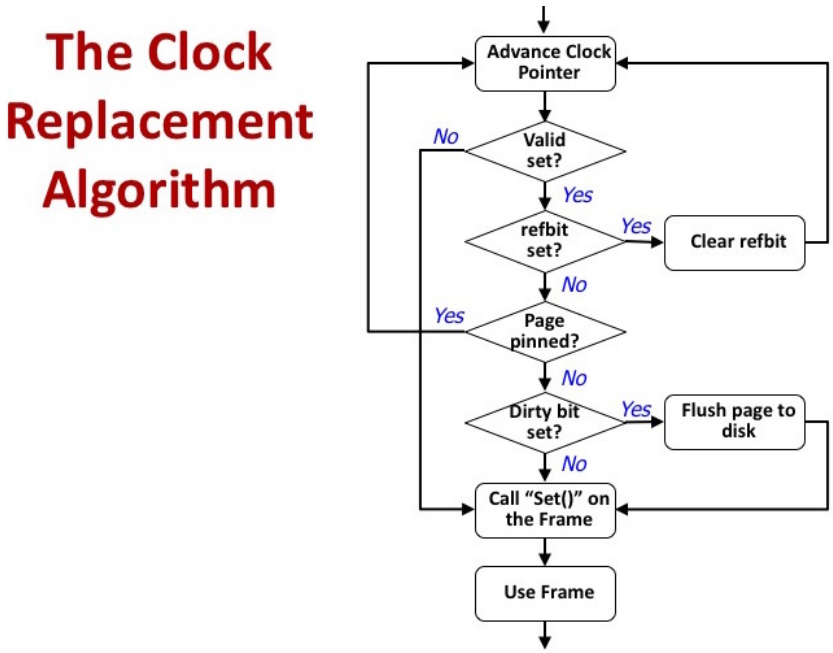


Figure 2: The Clock Replacement Algorithm

Here is the definition of the hash table.

```
class BufHashTbl
{
  private:
    hashBucket** ht; // pointer to actual hash table
    int HTSIZE;
    int hash(const File* file, const PageId pageNo);  //returns a value
        between 0 and HTSIZE-1
  public:
    BufHashTbl(const int htSize); // constructor
    ~BufHashTbl(); // destructor

    // insert entry into hash table mapping (file,pageNo) to frameNo
    void insert(const File* file, const int pageNo, const int frameNo);

    // Check if (file,pageNo) is currently in the buffer pool (ie. in
    // the hash table. If so, return the corresponding frame number in frameNo
    void lookup(const File* file, const int pageNo, int& frameNo);

    // remove entry obtained by hashing (file,pageNo) from hash table.
    void remove(const File* file, const int pageNo);
};
```

The BufDesc Class. The BufDesc class is used to keep track of the state of each frame in

the buffer pool. It is defined as follows.

First notice that all attributes of the BufDesc class are private and that the BufMgr class is defined to be a friend. While this may seem strange, this approach restricts access to BufDesc's private variables to only the BufMgr class. The alternative (making everything public) opens up access too far.

The purpose of most of the attributes of the BufDesc class should be pretty obvious. The dirty bit, if true indicates that the page is dirty (i.e. has been updated) and thus must be written to disk before the frame is used to hold another page. The pinCnt indicates how many times the page has been pinned. The refbit is used by the clock algorithm. The valid bit is used to indicate whether the frame contains a valid page. It is not necessary to implement any methods in this class. However you are free to augment it in any way if you wish to do so.

```
class BufDesc {
    friend class BufMgr;
  private:
    File* file;   // pointer to file object
    PageId pageNo;  // page within file
     FrameId frameNo;   // buffer pool frame number
    int pinCnt;     // number of times this page has been pinned
    bool dirty;   // true if dirty; false otherwise
    bool valid;   // true if page is valid
    bool refbit;    // true if this buffer frame been referenced recently

    void Clear();   // initialize buffer frame
    void Set(File* filePtr, PageId pageNum); //set BufDesc member variable
       values
    void Print()    //Print values of member variables
    BufDesc();    //Constructor
};
```

The BufMgr Class. The BufMgr class is the heart of the buffer manager. This is where you should write your new code for this project.

```
class BufMgr
{
  private:
    FrameId clockHand;  // clock hand for clock algorithm
    BufHashTbl *hashTable;  // hash table mapping (File, page) to frame number
    BufDesc *bufDescTable;  // BufDesc objects, one per frame
    std::uint32_t numBufs;  // Number of frames in the buffer pool
    BufStats bufStats;    // Statistics about buffer pool usage

   // allocate a free frame using the clock algorithm
  void allocBuf(FrameId & frame);
  void advanceClock();  //Advance clock to next frame in the buffer pool
```

```
  public:
    Page *bufPool;      // actual buffer pool

    BufMgr(std::uint32_t bufs); // Constructor
    ~BufMgr();          // Destructor

    void readPage(File* file, const PageId PageNo, Page*& page);
    void unPinPage(File* file, const PageId PageNo, const bool dirty);
    void allocPage(File* file, PageId& PageNo, Page*& page);
    void disposePage(File* file, const PageId pageNo);
    void flushFile(const File* file);
};
```

This class is defined as follows:

`BufMgr(const int bufs)`
This is the class constructor. Allocates an array for the buffer pool with bufs page frames and a corresponding BufDesc table. The way things are set up all frames will be in the clear state when the buffer pool is allocated. The hash table will also start out in an empty state. We have provided the constructor.

`~BufMgr()`
Flushes out all dirty pages and deallocates the buffer pool and the BufDesc table.

`void advanceClock()`
Advance clock to next frame in the buffer pool.

`void allocBuf(FrameId& frame)`
Allocates a free frame using the clock algorithm; if necessary, writing a dirty page back to disk. Throws BufferExceededException if all buffer frames are pinned. This private method will get called by the readPage() and allocPage() methods described below. Make sure that if the buffer frame allocated has a valid page in it, you remove the appropriate entry from the hash table.

`void readPage(File* file, const PageId PageNo, Page*& page)`
First check whether the page is already in the buffer pool by invoking the lookup() method, which may throw HashNotFoundException when page is not in the buffer pool, on the hashtable to get a frame number. There are two cases to be handled depending on the outcome of the lookup() call:

- Case 1: Page is not in the buffer pool. Call allocBuf() to allocate a buffer frame and then call the method file->readPage() to read the page from disk into the buffer pool frame. Next, insert the page into the hashtable. Finally, invoke Set() on the frame to

set it up properly. Set() will leave the pinCnt for the page set to 1. Return a pointer to the frame containing the page via the page parameter.

- Case 2: Page is in the buffer pool. In this case set the appropriate refbit, increment the pinCnt for the page, and then return a pointer to the frame containing the page via the page parameter.

`void unPinPage(File* file, const PageId PageNo, const bool dirty)`
Decrements the pinCnt of the frame containing (file, PageNo) and, if dirty == true, sets the dirty bit. Throws PAGENOTPINNED if the pin count is already 0. Does nothing if page is not found in the hash table lookup.

`void allocPage(File* file, PageId& PageNo, Page*& page)`
The first step in this method is to to allocate an empty page in the specified file by invoking the file->allocatePage() method. This method will return a newly allocated page. Then allocBuf() is called to obtain a buffer pool frame. Next, an entry is inserted into the hash table and Set() is invoked on the frame to set it up properly. The method returns both the page number of the newly allocated page to the caller via the pageNo parameter and a pointer to the buffer frame allocated for the page via the page parameter.

`void disposePage(File* file, const PageId pageNo)`
This method deletes a particular page from file. Before deleting the page from file, it makes sure that if the page to be deleted is allocated a frame in the buffer pool, that frame is freed and correspondingly entry from hash table is also removed.

`void flushFile(File* file)`
Should scan bufTable for pages belonging to the file. For each page encountered it should: (a) if the page is dirty, call file->writePage() to flush the page to disk and then set the dirty bit for the page to false, (b) remove the page from the hashtable (whether the page is clean or dirty) and (c) invoke the Clear() method of BufDesc for the page frame.

Throws PagePinnedException if some page of the file is pinned. Throws BadBufferException if an invalid page belonging to the file is encountered.

GETTING STARTED

When you decompress the folder at `http://cseweb.ucsd.edu/classes/sp21/cse132C-a/downloads/BufMgr.zip`, you will have a directory named *bufmgr*. In this directory, you will find the following files:

- `Makefile` : A make file. You can make the project by typing `make` on the shell.
- `main.cpp` : Driver file. Shows how to use File and Page classes. Also contains simple test cases for the Buffer manager. You must augment these tests with your more rigorous test suite.

- `buffer.h` : Class definitions for the buffer manager
- `buffer.cpp`: Skeleton implementation of the methods. Provide your actual implementation here.
- `bufHash.h` : Class definitions for the buffer pool hash table class. Do not change.
- `bufHash.cpp` : Implementation of the buffer pool hash table class. Do not change.
- `file.h` : Class definitions for the File class. You should not change this file.
- `file.cpp` : Implementations of the File class. You should not change this file.
- `file_iterator.h` : Implementation of iterator for pages in a file. Do not change.
- `page.h` : Class definition of the page class. Do not change.
- `page.cpp` : Implementation of the page class. Do not change.
- `page_iterator.h`: Implementation of iterator for records in a page.
- `exceptions directory`: Implementation of all your exception classes. Feel free to add more files here if you need to.

Coding and Testing. We have defined this project so that you can understand and reap the full benefits of object-oriented programming using C++. Your coding style should continue this by having well-defined classes and clean interfaces. Reverting to the C (low-level procedural) style of programming is not recommended and will be penalized. The code should be well-documented, using Doxygen style comments. Each file should start with your name and student id, and should explain the purpose of the file. Each function should be preceded by a few lines of comments describing the function and explaining the input and output parameters and return values.

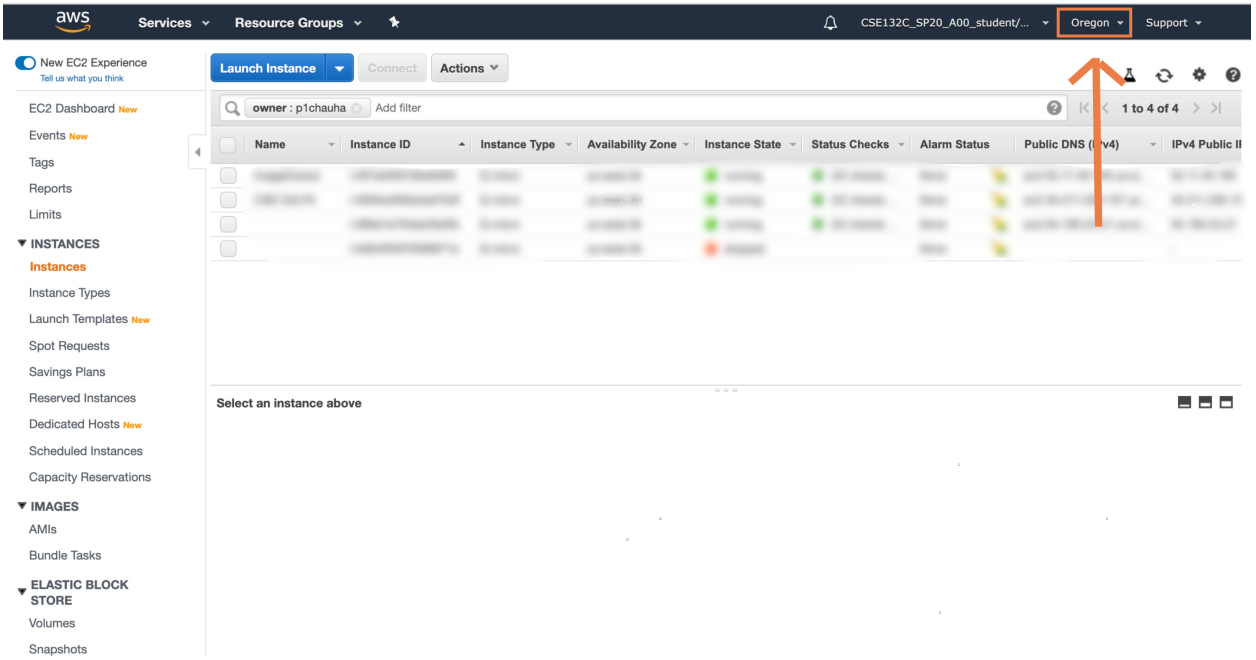
DELIVERABLES

You are required to submit all the necessary material in a single zipped folder (use GZip or WinZip). Your folder should include **only the source code files** (no binaries). We will compile your buffer manager implementation, link it with our test driver, and run tests. Since we are supposed to be able to test your code with any valid driver, IT IS VERY IMPORTANT TO BE FAITHFUL TO THE EXACT DEFINITIONS OF THE INTERFACES as specified here. If you alter these interfaces and your code does not compile, you will be penalized. Email your zipped folder to the TA before 11:59PM of the deadline date. The latest version you email will be used for evaluation. Name the zipped folder as BufMgrSubmission-[LastName].zip, where [LastName] is your last name; if your team has two students, concatenate both of your last names.

AWS EC2 SETUP

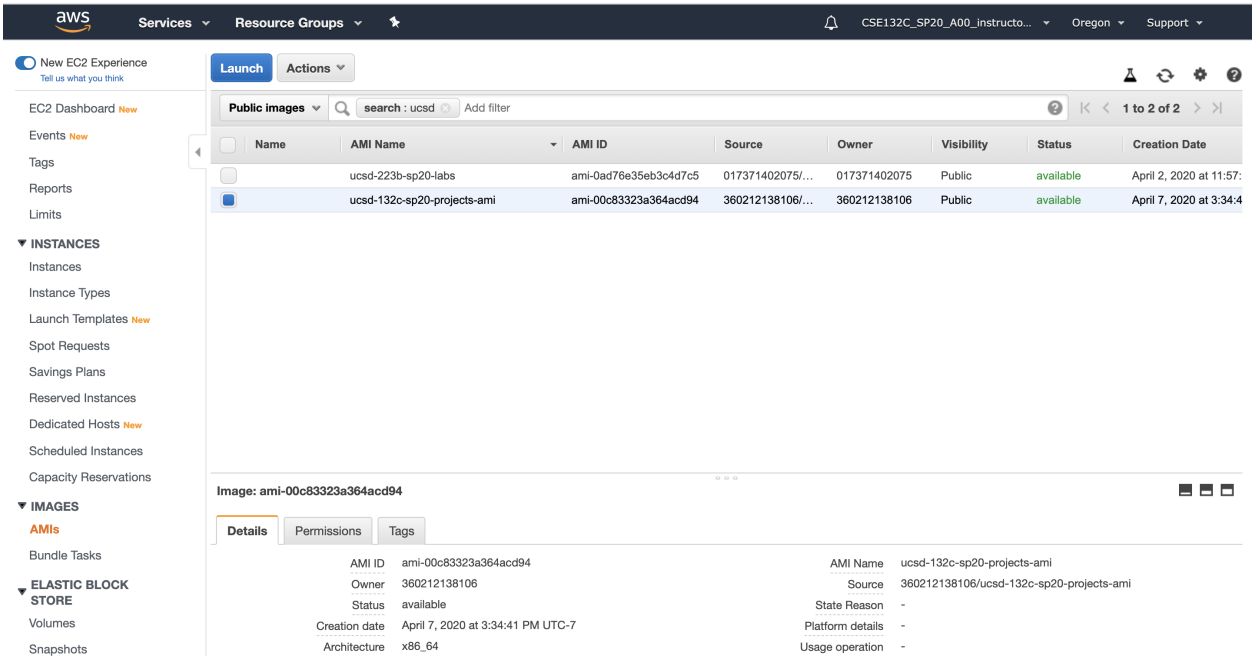
1. Go to `http://awsed.ucsd.edu/` and select **CSE132C_SP20_A00** to open the AWS console. This is a restricted account and has minimal permissions, so make sure you follow all steps properly, otherwise you might see errors.

2. Make sure your region is **Oregon**(us-west-2). You can find the region on the top-right of the AWS console.



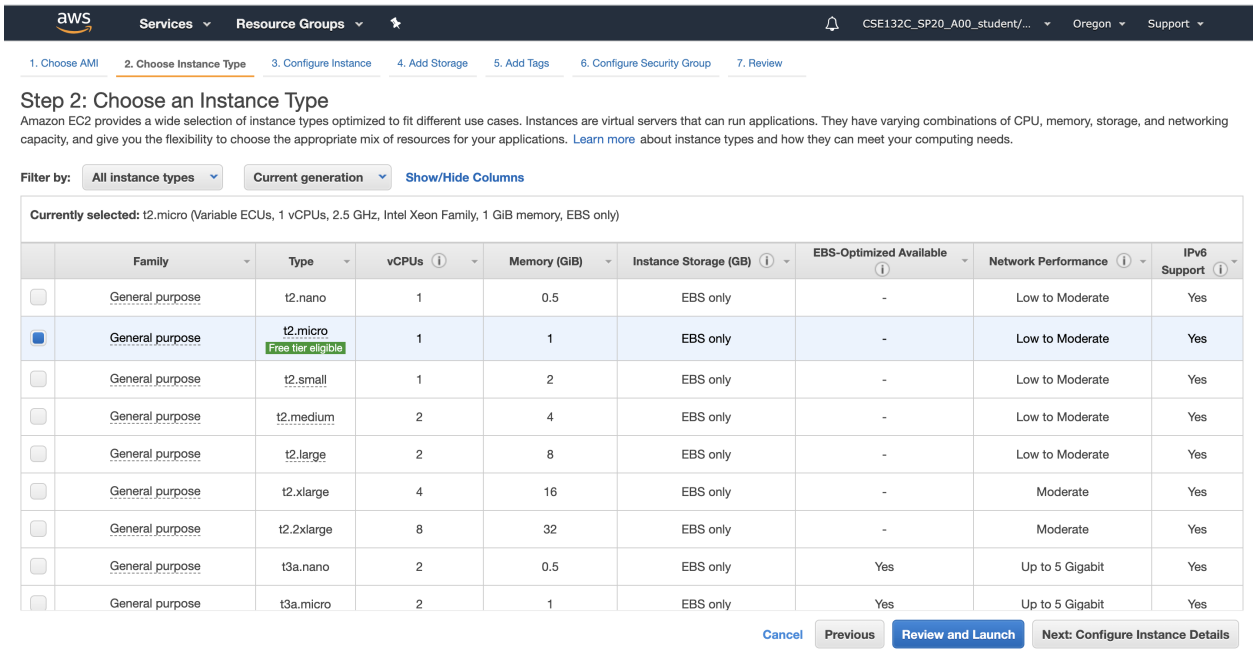
3. Locate our AMI.

    - From the navigation bar, choose AMIs.
    - In the menu next to the search bar, choose Public Images and search "ucsd".
    - Our image named **ucsd-132c-sp20-projects-ami** should show up. If not, double-check your region once again and let us know.

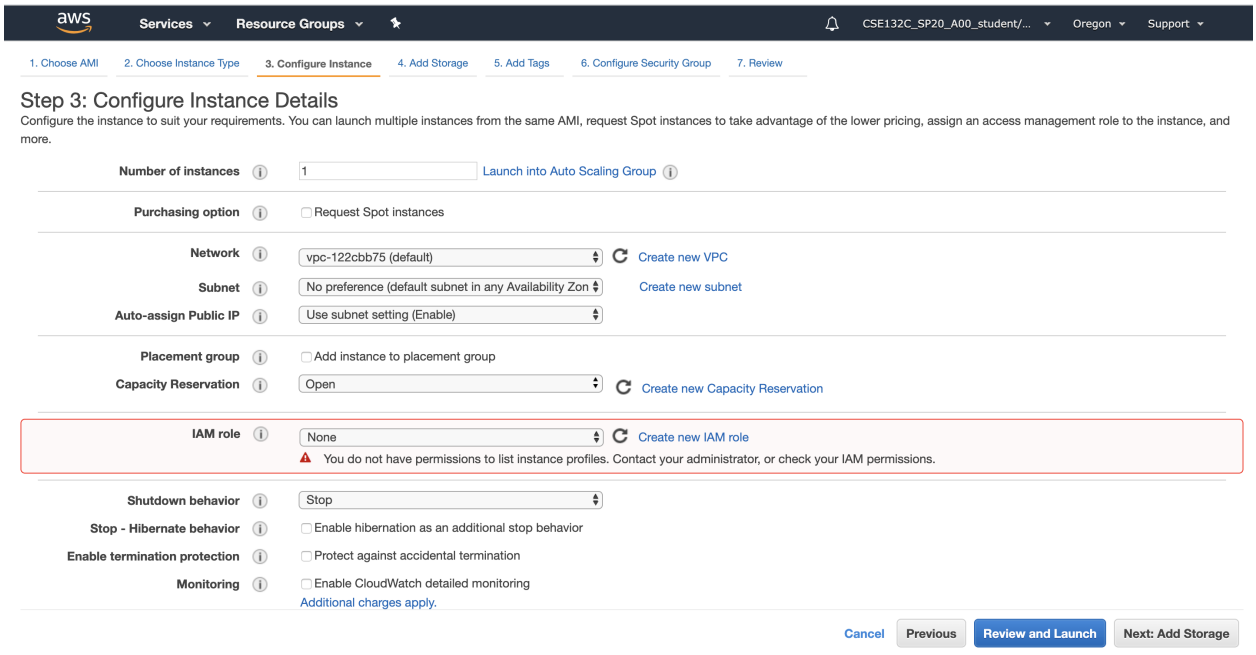


4. Select the Image and click "Launch".

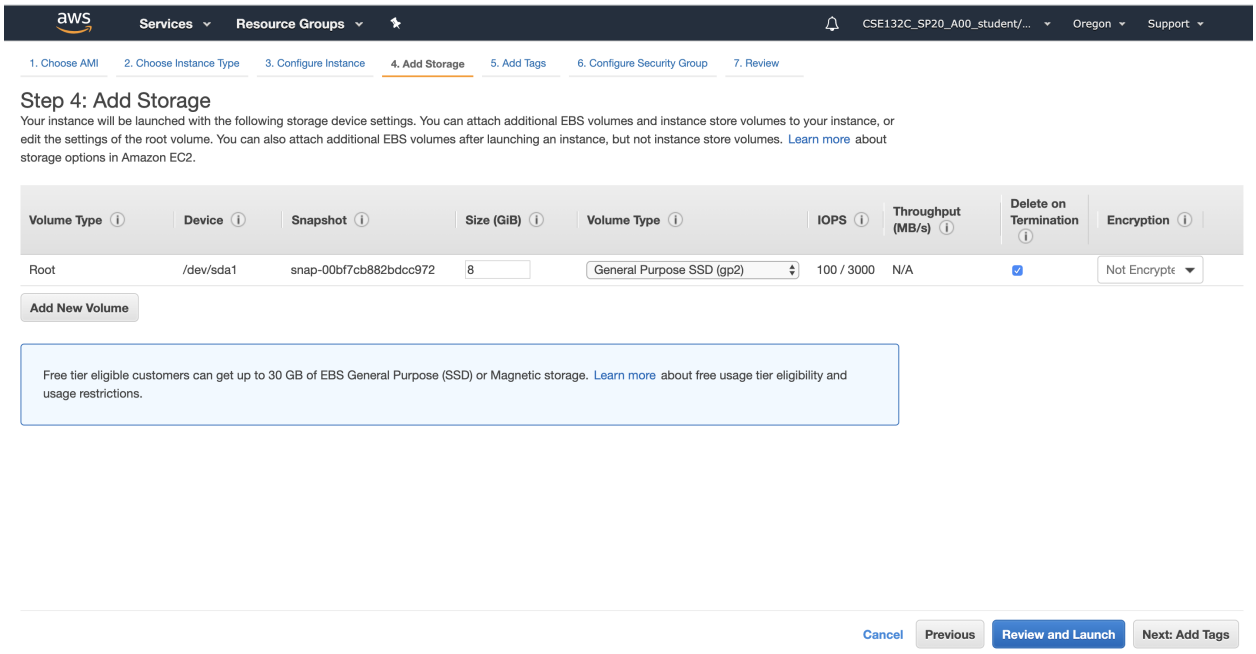
    - Step 2: Keep the pre-selected free-tier instance.



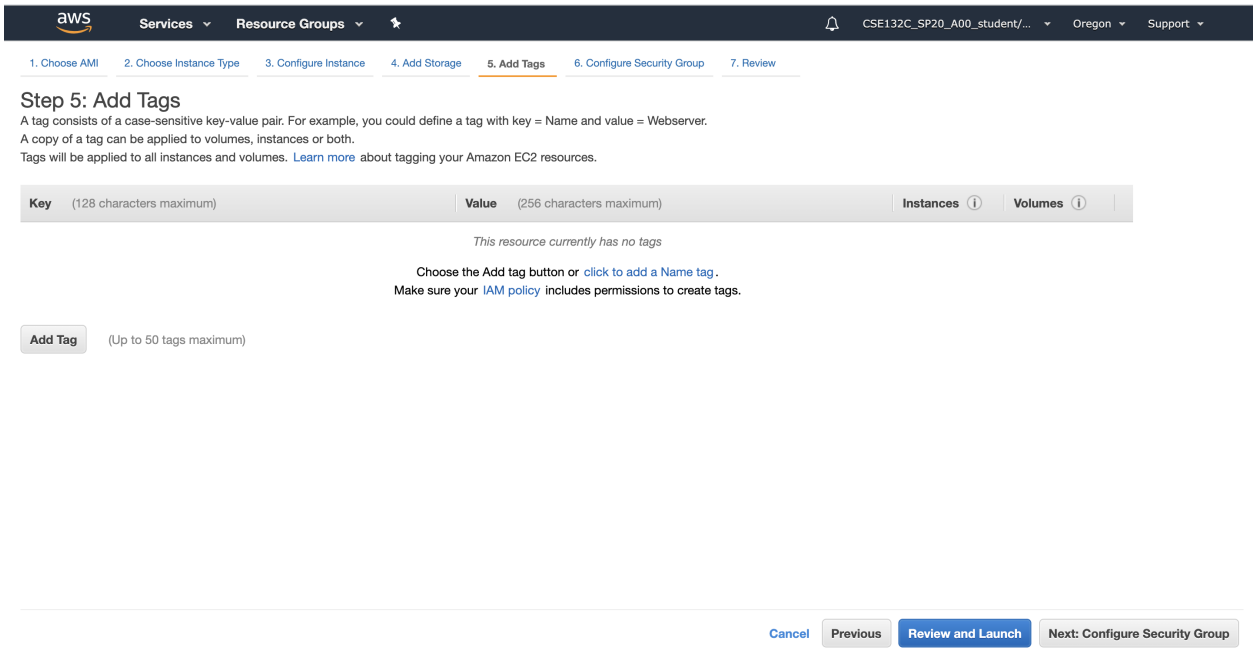
- Step 3: Keep defaults, and click "Next".



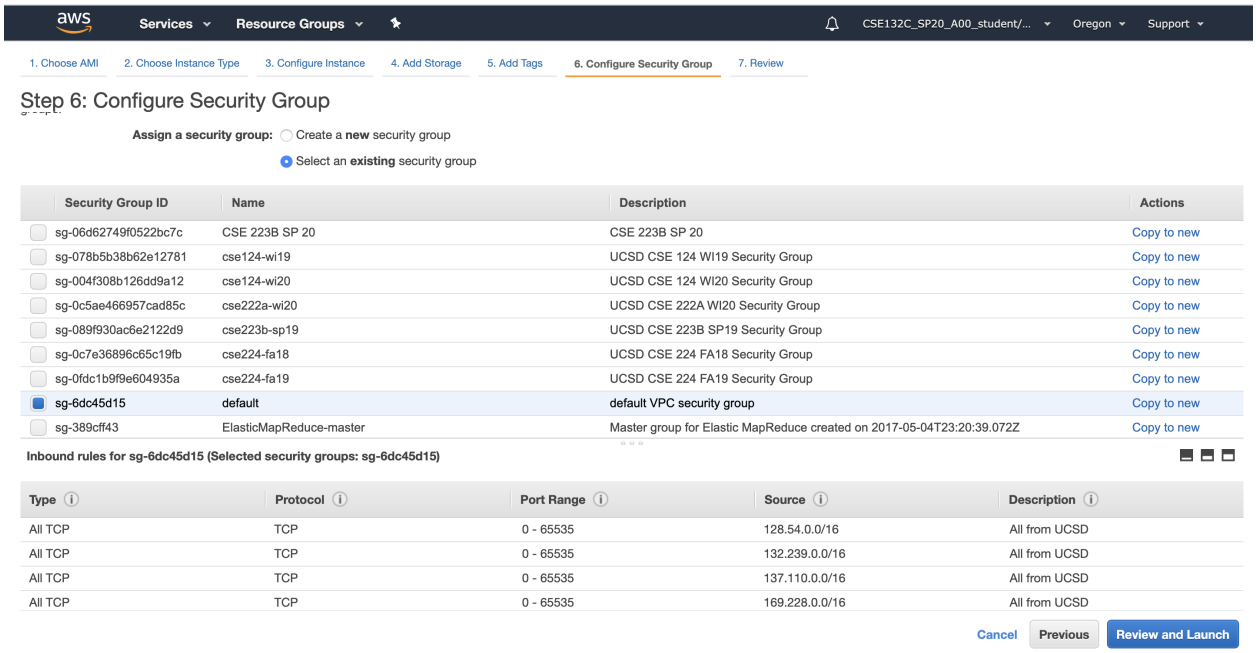
- Step 4: Keep defaults, and click "Next".



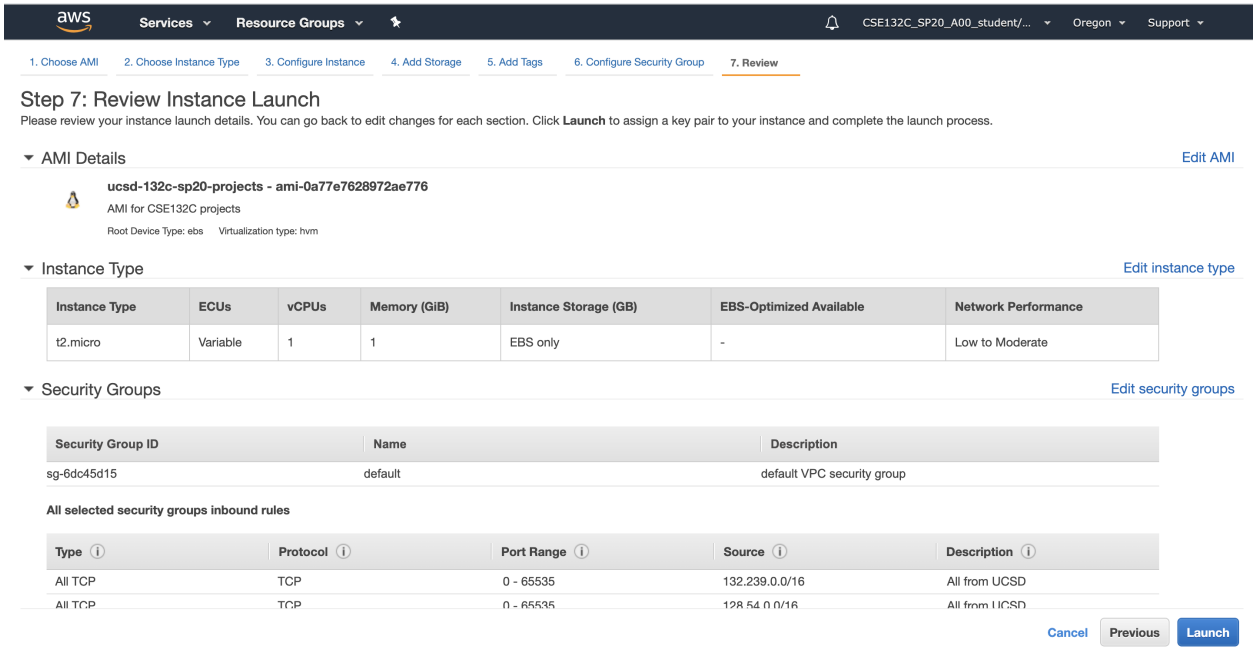
- Step 5: Keep defaults, and click "Next".



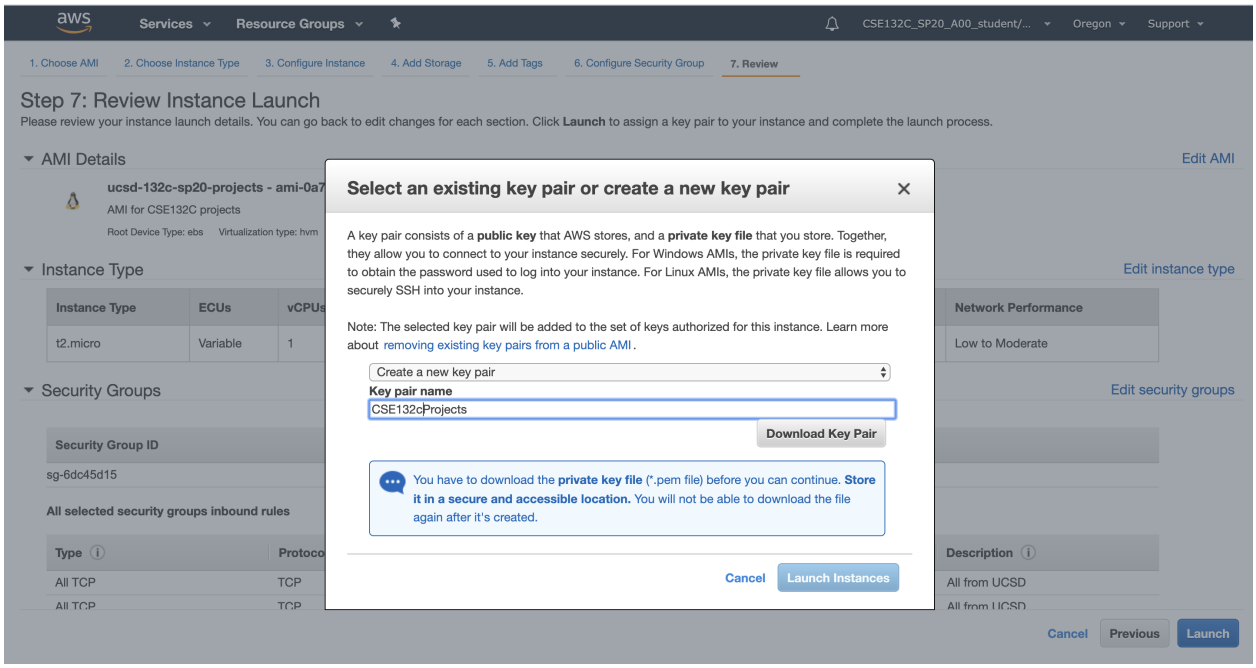
- Step 6: Choose an existing security group. Find the security group named **default** (with id: sg-6dc45d15) and use that one. You will not have permissions for most other groups.



- Step 7: Keep defaults, and click "Launch".

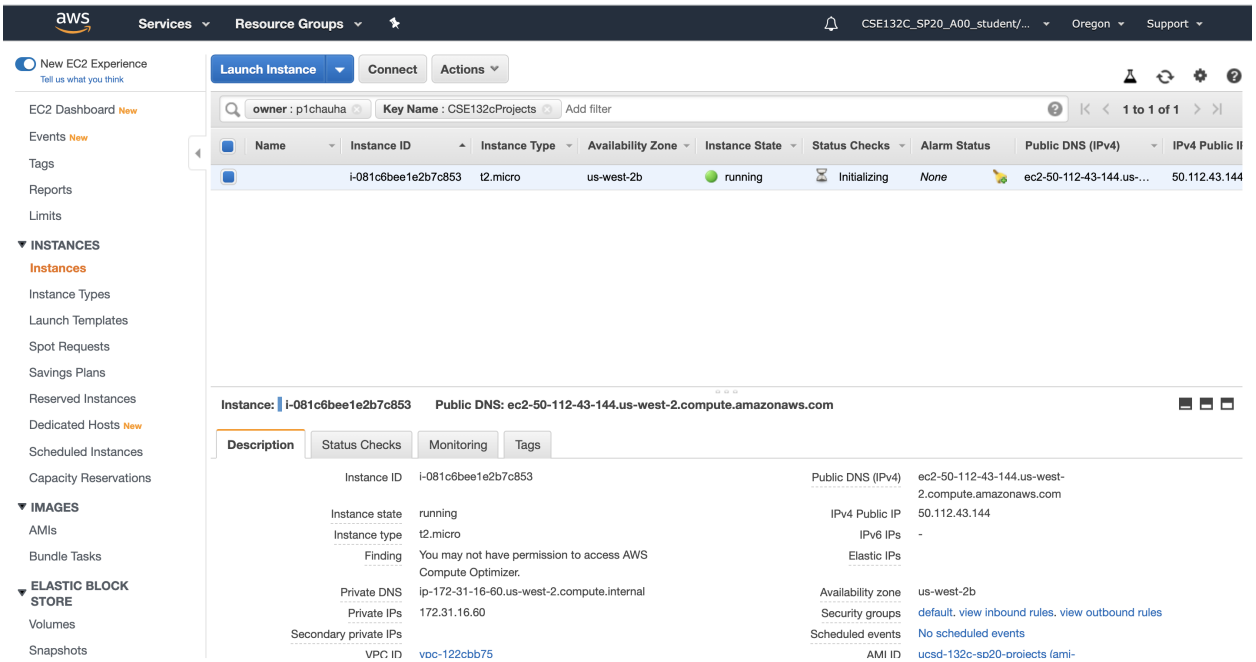


- Create a new key-pair with a name recognizable to you. Make sure to download and save it properly.



- Proceed with launch.

5. Once launched, go to the EC2 dashboard. There will a big list of instances, **you can find yours by the "Owner", "Key Name" or "Launch Time" columns**. Use your username for the "Owner" field and the name of the permissions file you downloaded earlier for "Key Name".



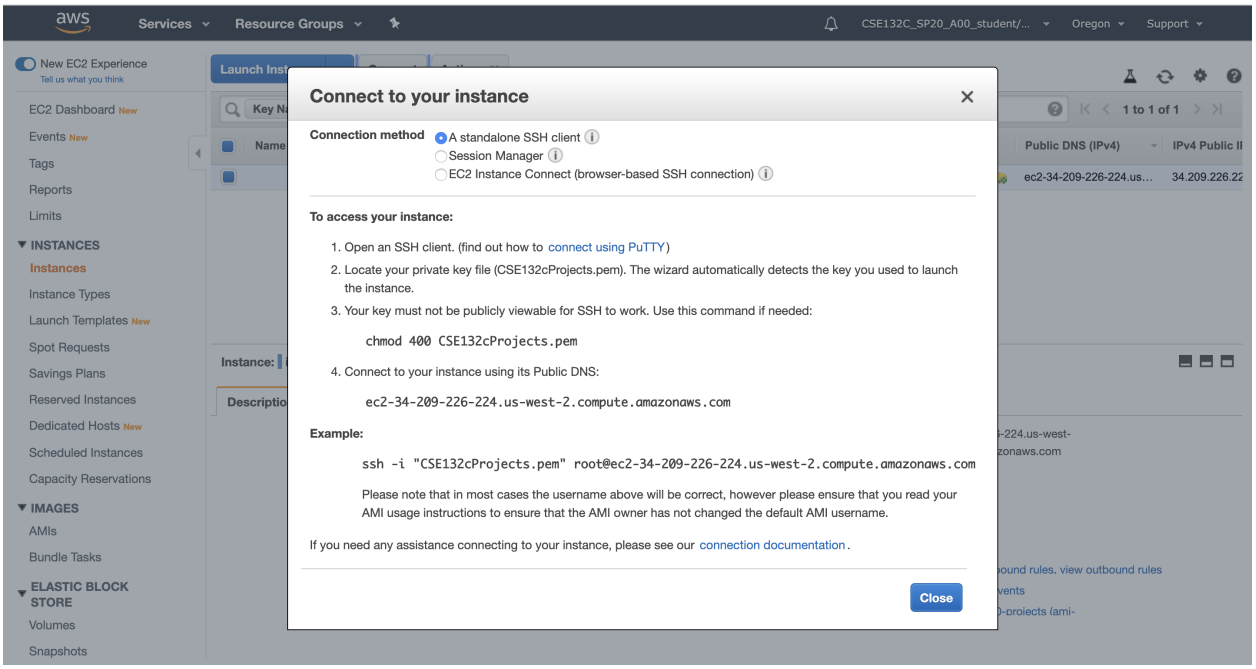
6. You can then ssh to your instance using the key you downloaded and the public DNS of your instance. Click on the **Connect** button to see the instructions on how to ssh. Few important things to note:

   - **Make sure you are connected to the UCSD VPN, the security group does not allow traffic from anywhere else.** You can find the instructions to connect to UCSD VPN here - `https://blink.ucsd.edu/technology/network/connections/off-campus/VPN/`
   - Give minimal permissions to the downloaded pem file using:

     ```
     chmod 400 <path-to-pem-file>
     ```

   - **Login as user *ubuntu*** (instead of *root* as shown in the screenshot below) i.e. do this:

     ```
     ssh -i <path-to-pem-file> ubuntu@<public-DNS>
     ```


aws
Services
Resource Groups
CSE132C_SP20_A00_student/...
Oregon
Support
New EC2 Experience
Tell us what you think
EC2 Dashboard New
Events New
Tags
Reports
Limits
INSTANCES
Instances
Instance Types
Launch Templates New
Spot Requests
Savings Plans
Reserved Instances
Dedicated Hosts New
Scheduled Instances
Capacity Reservations
IMAGES
AMIs
Bundle Tasks
ELASTIC BLOCK STORE
Volumes
Snapshots
Launch Inst
Key Na
Name
1 to 1 of 1
Public DNS (IPv4)
IPv4 Public II
ec2-34-209-226-224.us...
34.209.226.22
Instance:
Descriptio
Connect to your instance
Connection method
A standalone SSH client
Session Manager
EC2 Instance Connect (browser-based SSH connection)
To access your instance:
1. Open an SSH client. (find out how to connect using PuTTY)
2. Locate your private key file (CSE132cProjects.pem). The wizard automatically detects the key you used to launch the instance.
3. Your key must not be publicly viewable for SSH to work. Use this command if needed:
chmod 400 CSE132cProjects.pem
4. Connect to your instance using its Public DNS:
ec2-34-209-226-224.us-west-2.compute.amazonaws.com
Example:
ssh -i "CSE132cProjects.pem" root@ec2-34-209-226-224.us-west-2.compute.amazonaws.com
Please note that in most cases the username above will be correct, however please ensure that you read your AMI usage instructions to ensure that the AMI owner has not changed the default AMI username.
If you need any assistance connecting to your instance, please see our connection documentation.
Close