Lab 9

Introduction

This lab is focused on cohesivity and coupling of modules in Python and Java projects using tools such as `pydeps` and `LCOM` .

Cohesion

Cohesiveness is a measure of how much do the functions in a module have in common, and how much we benefit from modularisation being done in that way.
The hierarchy of cohesiveness, from low to high is :

1. coincidental cohesion : random collections of functions
2. logical cohesion : functions perform similar, or interdependent operations
3. temporal cohesion : functions are all run in a particular time frame.
4. procedural cohesion : the functions achieve individual steps or phases of some algorithm, which may still have some complicated control flow.
5. communication cohesion : the functions query and update the same data (global variables and such)
6. sequential cohesion : the functions are steps in a squence of steps ; not just any algorithm, with complicated control flow .
7. functional cohesion : the elements of a module cooperate to achieve a single common goal, which is the goal of the module. (example : managing an employee's pay-roll) . We can describe such a goal in one sentence.

Coupling

Coupling between 2 modules is a measure of how interdependent they are. The levels of coupling are (from low to high) :

1. data coupling : there is transfer of primitive data types between the modules.
2. stamp coupling : there is transfer of complex data types, such as objects and structs
3. control coupling : the data shared aren't just values, but also flags
4. common coupling : some global data (variables) are shared between the modules
5. content coupling : code is shared between functions of two modules. This violates the principle of information hiding that a module is supposed to have.

We will be dealing mostly with content coupling.

Layered design

Just as hardware modules, software modules with functional cohesion have a concept of

- fan-in : The number of modules that depend on this module
- fan-out : The number of modules this module depends on
- depth : number of modules used in a sequence to accomplish the main task.
- width : The span of the layered design

A good design typically has low fan-out (generally related to low functional cohesion) and high fan-in (code reuse) . This also makes it easy to debug in terms of dependencies.

Thesse dependencies can be visualised using Module Graphs.

PyDeps

`pydeps` is a python module for dependency visualisation. It finds dependencies using the `import` op-codes in the compiled bytecode (`.pyc` files) for the Python VM.

It uses a scoring function called "Bacon" which lets us filter out the modules that are a given number of hops away from our module of interest.

It also allows for clustering, folding of external modules, cycle detection, etc.

`pydeps` also outputs JSON as an intermediate format.

Lack of cohesion in methods (LCOM)

LCOM is a tool for analysing dependencies for Java projects.
It provides five versions of LCOM scoring metrics : LCOM1,LCOM2,LCOM3,LCOM4,LCOM5

and one new metric called YALCOM.

Yet another Lack of cohesion in methods (YALCOM)

For a type/class t which has non-zero number of methods and isn't just an interface, we compute its LCOM value by this algorithm :

- initialise $G = (V, E)$ as an empty graph.
- $V := V \cup t.\text{methods}()$
- $V := V \cup t.\text{attributes}()$
- $t_0 := t.\text{supertype}()$
- $V := V \cup t_0.\text{attributes}()$
- for m in $t.\text{methods}()$:
  - for a in $m.\text{attributesAccessed}()$:
    - $E := E \cup \{(m, a)\}$
  - for m' in $m.\text{methodInvocatons}()$:
    - $E := E \cup \{(m, m')\}$
- $d = G.\text{disconnectedMethods}()$
- if $d = 1$: return 0
- else : return $d/|t.\text{methods}()|$

Note that here, we will disregard the static attributes just as the compiler does.

In short, create the dependency graph G between methods and (non-static) attributes.
Then find the number of connected components that have at least one method in it, namely $d = G.\text{disconnectedMethods}()$.
This is similar to the LCOM4 metric, which is essentially the number of connected components (including non-method components).
If d is less than some fixed threshold l then return 0, else return that number, divided by number of methods.

For a type with no cohesion between the methods, we would have the value 1.
And for a very cohesive set of methods, where every method interacts with ever other method, by either calling it, or modifying some shared data, we have $d = 1$ and thus, LCOM value of 0.

Methodology

Project selection

The real world Python project that I'll be using for this lab is Pandas (44.9K stars), since it has a lot of modules, and is a rather big project.
Similar to pandas, JTableSaw (3.6K stars) is a Java library for data manipulation and visualisation.
This, just like Pandas, has a lot of modules. So, I'll be using it for this lab.

Depenency Graph analysis

Instability

To rank the modules based on how likely they are to be have errors introduced due to changes in other modules, I'll be taking the same approach that is taken by the package module-coupling-metrics . That is, we rank based on

$$\text{instability} = \frac{\text{fan out}}{\text{fain in} + \text{fain out}}$$

So, the modules with low instability are less prone to have errors after a commit.

degree of coupling

Since there is no way to find the actual degree of coupling between two modules using just the JSON output, I'll use the output of the original PageRank algorithm to find how much a particular module is coupled with the rest of the modules. The modules which are ranked higher are more coupled. These are usually modules that have low fan-out and high fan-in. This will be done using the `networkx` Python package.

Cycles

To find all the cycles in a graph, we cannot use a simple algorithm like DFS or BFS. Instead, we have to either resort to finding a cycle-basis, for undirected graphs, or the simple cycles (with no repeated nodes) in a directed graph. This is a hard problem, and is achieved using the `networkx` Python package.

Depth

Since there are cycles in the dependency graphs, we cannot simply use the shortest path tree algorithm or such, to determine, at which level a module is.

For the sake of clarity, the outermost module, namely `__main__` will be assigned a depth 0, since it is closest to the end user. And modules that are more hidden, such as libraries for doing internal tasks, will have higher depth.
If there exists a cycle that has modules x, y in it, then the depths of x and y must be the same. Essentialy, for a group of nodes such that every node can be reached by every other node through some path, the depths must be the same. What we just described is known as a strongly connected component.
The Python library `networkx` has the function `condensation` which will allow us to do find and connect the strongly connected components. Then, we can simply do a shortest path tree approach on the condensed graph to find the depths.

Dependency Impact Assessment

We can model this using population growth dynamics, namely using a transition matrix. At each step, we'll have account of the exected value of functional changes in a module due to the changes in initial module. Then, every iteration, all the changes, in every module propogate themselves. This keeps on going.
Here are a few rules that are followed during progogation of changes.

1. Every change in a module triggers changes in dependent modules only one time, and with a probability p for every edge, where p is some hyper-parameter.
2. Every new change is propogated as well.
3. The sum of changes in all the steps for a module is finally how much it will change.

First, let's cosider the transition matrix $P = pA$ where A is the adjacency matrix for the dependency graph, with dependents on rows and dependencies on columns.
Consider the intial change $c_0 = [\delta_{s,i}]_i$ if module s was changed.
This induces changes $c_1 = Pc_0$, which further induce changes $c_2 = Pc_1 = P^2c_1$ and so on.
In general, $c_n = P^nc_0$. The sum of all these changes is

$$S = \lim_{N\to\infty} \sum_{n=0}^{N-1} P^n c_0$$

Notice that $c_n \geq \vec{0}$, i.e. it has positive elements

Also, when $1/p$ is more than the highest fan-in value f, then we necessarily have $|c_n|_1 \leq fp|c_{n-1}|_1 \implies \lim_{n\to\infty} c_n = 0$. We also have

$$I - P^N = (I - P)(\sum_{n=0}^{N-1} P^n) \implies$$
$$c_0 - P^N c_0 = (I - P)(\sum_{n=0}^{N-1} P^n)c_0 \implies$$
$$c_0 = (I - P)(\sum_{n=0}^{N-1} P^n)c_0 + c_n \ \forall N$$

So, taking the limit as $N \to \infty$, we get

$$c_0 = (I - P)S$$

Of course, sometimes the matrix $I - P$ may not be invertible. In such a case, most we can do if apply a pseudo-inverse, that is, project the vector c_0 onto the span of $(I - P)$ and then solve for S. This is still ok, as long as it gives us a sensible output.

Thus, our formula for changes becomes

$$S = (X^TX)^{-1}X^Tc_0 \text{ where } X = I - pA$$

So, the ith column of $(X^TX)^{-1}X^T$ tells us the effect of changing module i by one unit.
Let's take a row so that it becomes the ith row instead, and subtract the identity matrix from it, so that it doesn't account for the initial change.
Thus, we define the effect matrix as $((X^TX)^{-1}X^T)^T - I$

We can use this to figure out the modules that are most susceptible to change when a particular module changes. For sake of simplicity, let's only limit ourselves to 5 such modules.

We can also rank the modules based on the total amount of change they are likely to bring.

`analysis1.py`

All the above things are accomplised using this program :

```
import json
import pandas as pd
import networkx as nx
import numpy as np
import matplotlib.pyplot as plt
with open('/home/hp/STT/STTLab9/pandas_deps.json', 'r') as file:data = json.load(file)

print("Making Graph")
A = {x:data[x].get("imports",[]) for x in data} # Adjacency matrix
G = nx.DiGraph(A)
l = len(A)
print(l,"modules found")

print("Making DataFrame")
L = []
cols = ['name', 'fan-in', 'fan-out', 'bacon']
for x in data:
    y = data[x]
    z = [y['name'],len(y.get('imported_by', [])),len(y.get('imports', [])),y.get('bacon', 0)]
    L.append(z)
df = pd.DataFrame(L, columns=cols).dropna()

print("importance of a module")
ranks = nx.pagerank(G)
df["rank"] = [ranks[x] for x in df["name"].values]

print("instability")
df["instability"] = df["fan-out"]/(df["fan-out"] + df["fan-in"])
df.sort_values(by='instability', ascending=False, inplace=True)

print("saving")
df.to_csv('pandas_deps.csv', index=False)

print("Computing Cycles")
C = nx.simple_cycles(G)
C = [c for c in C if len(c) > 1] # list of all simple cycles
C = sorted(C,key=lambda c:len(c))
f = open("pandas_deps_cycles.txt",'w')
f.write("\n".join([" --> ".join(c) for c in C]))
f.close()

print("Unused or less used modules")
df.loc[(df["fan-in"]<=1).values].to_csv("pandas_deps_unused.csv", index=False)
```

```
print("calculating transition matrix")
modules = [x for x in A]
module_num = {x:i for i,x in enumerate(modules)}
p = 0.5/(1+df["fan-in"].max())
print("p is",p)
P = [[0]*l for i in range(l)]
print("memory assigned")
for x in A:
    for y in A[x]:
        P[module_num[x]][module_num[y]] = p
P = np.array(P)
print("P calculated")
X = np.identity(l) - P
print("X calculated. Shape:",X.shape)
d = np.linalg.det(X)
print("det(X) =",d)
if d !=0 :
    Xinv = np.linalg.inv(X)
    effect = Xinv.T
else:
    XTX = X.T @ X
    print("XTX calculated. Shape:",XTX.shape)
    XTXinv = np.linalg.inv(XTX)
    print("XTXinv calculated. Shape:",XTXinv.shape)
    XTXinvXT = XTXinv @ X.T
    effect = XTXinvXT.T
effect = effect - np.identity(l)
print("effect calculated. Shape:",effect.shape)
L = [["modules"] + modules]
for i in range(l):
    L.append(
        [modules[i]] +
        [str(x) for x in effect[i]]
        )

L = [",".join(row) for row in L]
L = "\n".join(L)
f = open('pandas_deps_effect.csv','w')
f.write(L)
f.close()

plt.imshow(effect,cmap="Grays")
plt.xticks(range(l),modules,rotation=90,size=6)
plt.yticks(range(l),modules,size=6)
plt.tight_layout()
plt.savefig("pandas_deps_effect.png",format="png")
plt.close()
```

```
print("getting ordering")
ordering = {}
for i in range(l):
    effects = effect[i]
    ind = sorted(list(range(l)),key= lambda j : effects[j],reverse=True)
    victims = [modules[j] for j in ind]
    ordering[modules[i]] = victims
total = [sum(row) for row in effect]
ord_tot = sorted(list(range(l)),key=lambda i:total[i],reverse=True)
ord_tot = [modules[i] for i in ord_tot]
ordering = {x:ordering[x] for x in ord_tot}

print("writing JSON string")
L = []
for x in ordering:L.append(repr(x) + " : " + repr(ordering[x]))
L = ",\n".join(L)
L = "{\n" + L + "\n}"
L = L.replace("'","\"")
f = open("pandas_deps_effect.json",'w')
f.write(L)
f.close()

print("condensation")
plt.figure()
H = nx.condensation(G)
nx.draw(H,with_labels=True)
plt.savefig("pandas_deps_cond.png",format="png")
plt.close()
f = open("pandas_deps_cond.json",'w')
groups = H.nodes.data()
L={x[0]:list(x[1]["members"]) for x in groups}
f.write(json.dumps(L,indent=4))
f.close()
```

Java Cohesion using LCOM

The project chosen is `tablesaw`. The command to run the archive `LCOM.jar` on this is

```
java -jar LCOM.jar -i tablesaw -o .
```

This outputs the CSV file `TypeMetrics.csv` in the working directy, but also deletes any other files (not folders) that it finds. So, I had to run this before anything else.

The columns of the CSV file are

- Project Name (`tablesaw`, for all entries)
- Package Name (file containing the type)
- Type Name (the name of the class)
- LCOM1 score
- LCOM2 score
- LCOM3 score
- LCOM4 score
- LCOM5 score
- YALCOM score

Classes with high LCOM values and Visualisation

A high LCOM value means that there is lack of cohesion between the methods in a class. This usually means that we should refactor the code to lower the LCOM/YALCOM value.

To find the classes with high LCOM values, we can use the script `analysis2.py`. This also finds the actual JAVA file that has the class, rather than the package name, which may or may not directly relate to source code location. This is possible pnly because of the directory structure that the developers are using.

I am also filtering out test cases, so that we can restrict our attention to only the class definitions.

Since an YALCOM value of -1 means that it wasn't possible to evaluate the score on the given type, I'm filtering out these cases as well.

This leaves us with about 250 types with a valid YALCOM score, in the file `TypeMetrics.csv`. Dealing with each of these is not possible. So, instead, I'll only present the source code of the classes with highest YALCOM values.

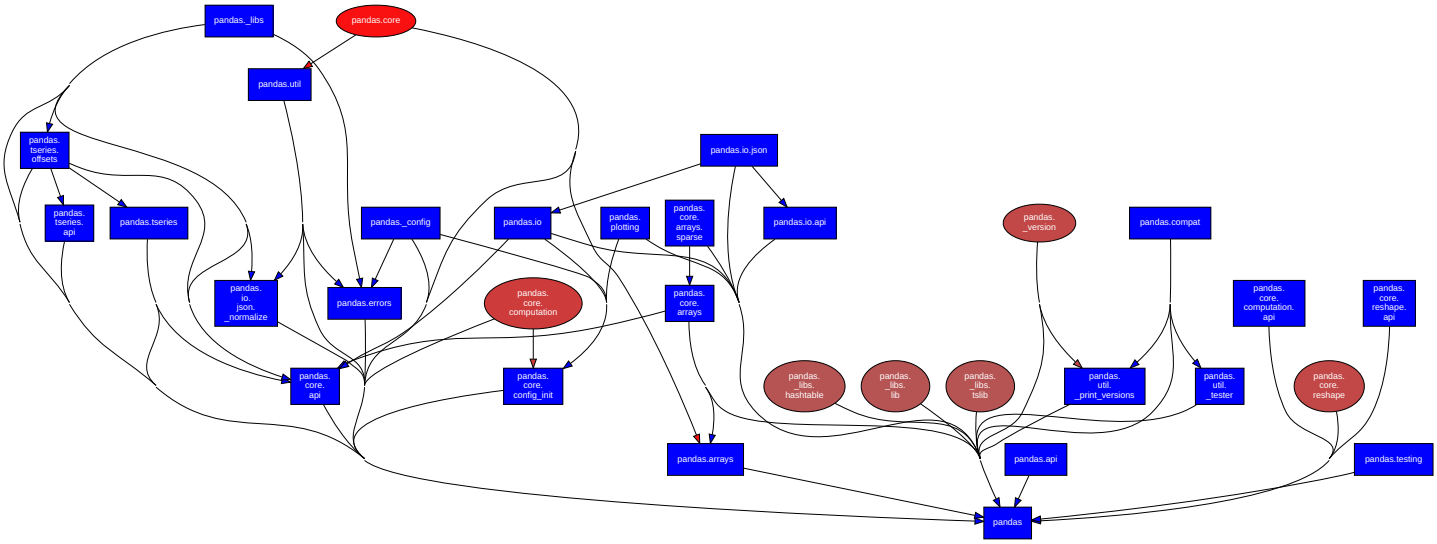
The script generates HTML tables to visualise it better.

analysis2.py

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import os,ast

def findfile(typename):
    pack = typename + ".java"
    os.system("find tablesaw -name " + pack + "> temp")
    f = open("temp",'r')
    s =f.read().strip()
    if "test" in s : s = ""
    f.close()
    return s.strip()

def getsource(file):
    os.system("cat " + file + "> temp")
    f =open("temp",'r')
    s = f.read()
    f.close()
    s = s.split("\n")
    s = [x for x in s if x.strip() and x.strip()[:6] != "import"]
    s = "\n".join(s)
    s = repr(s)
    return s

# Clean and find file names
df = pd.read_csv("TypeMetrics.csv")
df.drop("Project Name",axis=1,inplace=True)
TypeNames = df["Type Name"].values
Files = [repr(findfile(x)) for x in TypeNames]
df["file"] = Files
df.sort_values("YALCOM",inplace=True,ascending=False)
df = df.where(df["file"]!="''")
df = df.where(df["YALCOM"]>-0.5)
df.dropna(inplace=True)
df.to_csv("TypeMetricsClean.csv",index=False)
top5 = df.head().copy()

# write Top5.csv
files = top5["file"].values
codes = [getsource(file) for file in files]
top5["JAVA code"] = codes
req = ["Type Name","Package Name","JAVA code","LCOM1","LCOM2","LCOM3","LCOM4","LCOM5","YALCOM"]
top5 = top5.loc[:,req]
top5.to_csv("Top5.csv",index=False)

# Make html tables
head = "\n".join(["<tr>","\n".join(["<td>" + x + "</td>" for x in req[2:]]),"</tr>"])
L = ["<table>",head]
for row in top5.values:
    toadd = [
        f"<td>\nclass:{row[0]}<br>\npackage:{row[1]}<pre><small>\n" +
        ast.literal_eval(row[2]).replace("<","&lt;").replace(">","&gt;") +
        "\n</small></pre></td>"
    ] + [f"<td>{x}</td>" for x in row[3:]]
    toadd = ["<tr>"] + toadd + ["</tr>"]
    toadd = "\n".join(toadd)
    L.append(toadd)
L.append("</table>")
L = "\n".join(L)
f = open("Top5.html",'w')
f.write(L)
f.close()
```

Results

Pandas Dependency Graph



Notice that by default we have the value of `--max-bacon` set to 2. This causes `pydeps` to simplifiy the graph. Since we are already at a desirable complexity, I did not change it.

The same is also present as JSON in `pandas_deps.json` :


```
{
    "__main__": {
        "bacon": 0,
        "imports": [
            "pandas"
        ],
        "name": "__main__",
        "path": null
    },
    "pandas": {
        "bacon": 1,
        "imported_by": [
            "__main__",
            "pandas",
            "pandas._config",
            "pandas._libs",
.
.
.
    },
    "pandas.util._tester": {
        "bacon": 2,
        "imported_by": [
            "pandas"
        ],
        "imports": [
            "pandas",
            "pandas.compat"
        ],
        "name": "pandas.util._tester",
        "path": "/home/hp/.local/lib/python3.10/site-packages/pandas/util/_tester.py"
    }
}
```


We then use this and the script to generate the CSV file `pandas_deps.csv` :

```
name,fan-in,fan-out,bacon,rank,instability
__main__,0,1,0,0.008507799381363788,1.0
pandas.core.api,1,7,2,0.014532894371391245,0.875
pandas.core.config_init,1,6,2,0.014532894371391245,0.8571428571428571
pandas.errors,1,4,2,0.014532894371391245,0.8
.
.
```

The modules are already sorted using instability. So, from this, we can gather that `__main__` is the most unstable module, i.e. one that is most likely to have persistent errors.

Highly coupled modules

We can sort these according to the `rank` value generated by PageRank algorithm to get the modules that have highest coupling

The output is :

```
          name  fan-in  fan-out  bacon      rank  instability
        pandas      26       32      1  0.226826     0.551724
  pandas._libs       6        2      2  0.061934     0.250000
   pandas.core       9        0      2  0.052220     0.000000
     pandas.io       6        3      2  0.049354     0.333333
pandas.io.json       4        3      2  0.045530     0.428571
```

This makes sense as well, since `pandas` is the most important module for the project.

Cyclic dependencies

There are in total, 65 simple cycles reported by the script. These are :

```
pandas._libs --> pandas
pandas.io --> pandas
pandas.io --> pandas.io.json
pandas._config --> pandas
pandas.testing --> pandas
pandas.core.config_init --> pandas
pandas.tseries.offsets --> pandas
pandas.core.arrays --> pandas
pandas.core.arrays --> pandas.core.arrays.sparse
pandas.util._print_versions --> pandas
pandas.compat --> pandas
pandas.errors --> pandas
pandas.io.json --> pandas
pandas.tseries.api --> pandas
pandas.util._tester --> pandas
pandas.io.api --> pandas
pandas.tseries --> pandas
pandas.core.reshape.api --> pandas
pandas.arrays --> pandas
pandas.api --> pandas
pandas --> pandas.core.api
pandas --> pandas.core.arrays.sparse
pandas --> pandas.core.computation.api
pandas --> pandas.io.json._normalize
pandas --> pandas.plotting
pandas --> pandas.util
pandas._libs --> pandas --> pandas.core.api
pandas._libs --> pandas --> pandas.errors
pandas._libs --> pandas --> pandas.io.json._normalize
pandas._libs --> pandas --> pandas.tseries.offsets
```

```
pandas.io --> pandas --> pandas.core.api
pandas.io --> pandas --> pandas.core.config_init
pandas.io --> pandas --> pandas.io.api
pandas.io --> pandas --> pandas.io.json
pandas.io --> pandas.io.json --> pandas
pandas._config --> pandas --> pandas.core.config_init
pandas._config --> pandas --> pandas.errors
pandas.core.config_init --> pandas.plotting --> pandas
pandas.tseries.offsets --> pandas --> pandas.core.api
pandas.tseries.offsets --> pandas --> pandas.tseries
pandas.tseries.offsets --> pandas --> pandas.tseries.api
pandas.core.arrays --> pandas --> pandas.arrays
pandas.core.arrays --> pandas --> pandas.core.api
pandas.core.arrays --> pandas --> pandas.core.arrays.sparse
pandas.core.arrays --> pandas.core.arrays.sparse --> pandas
pandas.util._print_versions --> pandas.compat --> pandas
pandas.compat --> pandas --> pandas.util._tester
pandas.errors --> pandas.util --> pandas
pandas.io.json --> pandas --> pandas.io.api
pandas.tseries.api --> pandas.tseries --> pandas
pandas.tseries --> pandas --> pandas.core.api
pandas --> pandas.io.json._normalize --> pandas.util
pandas._libs --> pandas --> pandas.core.api --> pandas.tseries.offsets
pandas._libs --> pandas --> pandas.tseries --> pandas.tseries.offsets
pandas._libs --> pandas --> pandas.tseries.api --> pandas.tseries.offsets
pandas.io --> pandas --> pandas.io.api --> pandas.io.json
pandas.io --> pandas.io.json --> pandas --> pandas.core.api
pandas.io --> pandas.io.json --> pandas --> pandas.core.config_init
pandas.io --> pandas.io.json --> pandas --> pandas.io.api
pandas.tseries.offsets --> pandas --> pandas.core.api --> pandas.tseries
pandas.tseries.offsets --> pandas --> pandas.tseries.api --> pandas.tseries
pandas.core.arrays --> pandas.core.arrays.sparse --> pandas --> pandas.arrays
pandas.core.arrays --> pandas.core.arrays.sparse --> pandas --> pandas.core.api
pandas._libs --> pandas --> pandas.core.api --> pandas.tseries --> pandas.tseries.offsets
pandas._libs --> pandas --> pandas.tseries.api --> pandas.tseries --> pandas.tseries.offsets
```

Having so many cyclic dependencies between the modules is not a good thing. In fact, one of the strongly connected components of the dependency graph, namely the one with `pandas` module, has 25 modules, out of the otal of the 33 modules. This causes one change in a module to have effects on almost all the modules. We'll look at all of that soon.

Unused modules

Although there aren't any actual disconnected components (not considering `__main__` which is the entry point for the user), there are modules with very low fan-in. Namely these ;

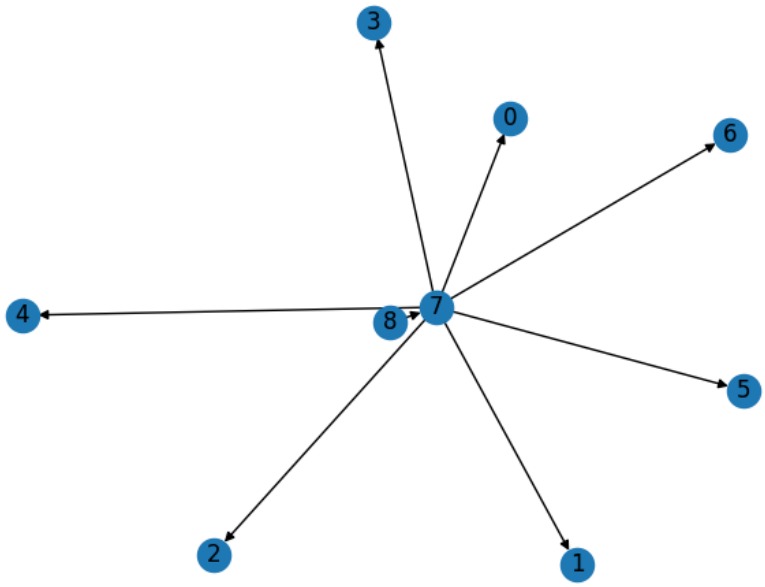
```
name,fan-in,fan-out,bacon,rank,instability
pandas.core.api,1,7,2,0.014532894371391245,0.875
pandas.core.config_init,1,6,2,0.014532894371391245,0.8571428571428571
pandas.errors,1,4,2,0.014532894371391245,0.8
pandas.util._print_versions,1,3,2,0.014532894371391245,0.75
pandas.tseries.api,1,3,2,0.014532894371391245,0.75
pandas.io.json._normalize,1,3,2,0.014532894371391245,0.75
pandas.io.api,1,3,2,0.014532894371391245,0.75
pandas.core.reshape.api,1,3,2,0.014532894371391245,0.75
pandas.core.computation.api,1,3,2,0.014532894371391245,0.75
pandas.arrays,1,3,2,0.014532894371391245,0.75
pandas.util._tester,1,2,2,0.014532894371391245,0.6666666666666666
pandas.testing,1,1,2,0.014532894371391245,0.5
pandas._libs.hashtable,1,0,2,0.014532894371391245,0.0
pandas._libs.lib,1,0,2,0.014532894371391245,0.0
pandas._libs.tslib,1,0,2,0.014532894371391245,0.0
```

Having so many modules with a fan-in of 1 seems like bad design, since there is no code reuse, and these modules could have been written directly inside the modules that import them, and it would have made no difference.

Depths of dependencies

The depth of a layered design is given by how many layers there are. But the layers don't interact in circular fashions usually, i.e. it's expected that feedback should not be present.

For this repository, it is rather hard to come up with such a layered design, on so, I depended on the condensation of the original graph :



Here, the nodes correspond to these strongly connected components :

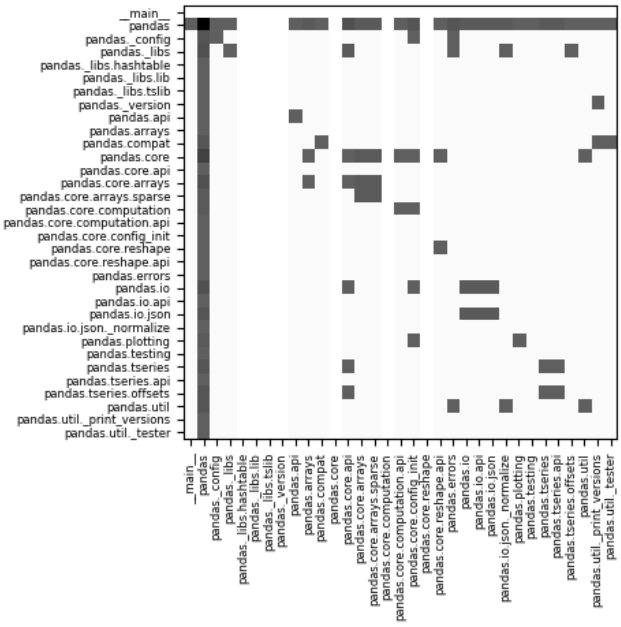
```
0: ["pandas._libs.hashtable"],
1: ["pandas._libs.lib"],
2: ["pandas._libs.tslib"],
3: ["pandas._version"],
4: ["pandas.core"],
5: ["pandas.core.computation"],
6: ["pandas.core.reshape"],
7: [
    "pandas._libs",
    "pandas.io",
    "pandas._config",
    "pandas.testing",
    "pandas.core.config_init",
    "pandas.tseries.offsets",
    "pandas.core.arrays",
    "pandas.compat",
    "pandas.tseries.api",
    "pandas.core.reshape.api",
    "pandas.arrays",
    "pandas",
    "pandas.core.computation.api",
    "pandas.io.json._normalize",
    "pandas.util",
    "pandas.core.arrays.sparse",
    "pandas.util._print_versions",
    "pandas.io.json",
    "pandas.tseries",
    "pandas.core.api",
    "pandas.errors",
    "pandas.util._tester",
    "pandas.io.api",
    "pandas.api",
    "pandas.plotting"
   ],
8: ["__main__"]
```

Thus, in reality, there are only 3 layers.

Dependency impact assessment

The value of effect matrix, as discussed in the methodology outputted by the program is stored in `pandas_deps_effect.csv` .

To help with visualisation, we have the heat map `pandas_deps_effect.png` :



I then used that to rank the modules based on the total expected change caused by an unit change in the module, and further, I sorted the receipients of the induced change by the expected amount of change they recieve. This gives us the JSON file `pandas_deps_effect.json` which has effect decreasing from top to bottom and left to right.

The top-left 5×5 entries are :

```
"pandas" :              ["pandas", "pandas.core.api","pandas.core.config_init",
                         "pandas.errors", "pandas.core.arrays.sparse"],
"pandas.core" :         ["pandas", "pandas.core.arrays", "pandas.core.arrays.sparse",
                         "pandas.core.api", "pandas.arrays"],
"pandas.io" :           ["pandas", "pandas.io.api", "pandas.io.json", "pandas.io","pandas.core.api"],
"pandas._libs" :        ["pandas", "pandas.core.api", "pandas.errors",
                         "pandas.io.json._normalize", "pandas._libs"],
"pandas.core.arrays" :  ["pandas", "pandas.core.arrays.sparse", "pandas.core.arrays",
                         "pandas.core.api", "pandas.arrays"]
```

Thus, these are the modules that have the most potntial to break the system if disturbed wrongly.

`LCOM.jar` output

The raw ouptut is stored in `TypeMetrics.csv` :

```
Project Name,Package Name,Type Name,LCOM1,LCOM2,LCOM3,LCOM4,LCOM5,YALCOM
tablesaw,tech.tablesaw.io.arrow,ArrowWriterTest,3.0,3.0,3.0,3.0,0.5,0.0
tablesaw,tech.tablesaw.io.arrow,ArrowReader,3.0,0.0,2.0,1.0,0.3333333333333333,0.0
tablesaw,tech.tablesaw.io.arrow,ArrowWriter,6.0,0.0,4.0,1.0,0.0,0.0
tablesaw,tech.tablesaw.io.html,HtmlWriterTest,5.0,4.0,5.0,5.0,0.8333333333333334,0.0
.
.
.
```

This output, when cleaned, and associated with file paths, gives us the CSV file `TypeMetricsClean.csv`

```
Package Name,Type Name,LCOM1,LCOM2,LCOM3,LCOM4,LCOM5,YALCOM,file
tech.tablesaw.columns.numbers,FloatColumnType,15.0,0.0,6.0,6.0,1.0666666666666669,1.0,'tablesaw/core/src/main/java/tech/tablesaw
tech.tablesaw.aggregate,DateAggregateFunction,6.0,0.0,4.0,4.0,0.0,1.0,'tablesaw/core/src/main/java/tech/tablesaw/aggregate/Date/
tech.tablesaw.aggregate,BooleanIntAggregateFunction,6.0,0.0,4.0,4.0,0.0,1.0,'tablesaw/core/src/main/java/tech/tablesaw/aggregate
.
.
.
```

High LCOM classes

Since it's hard to analyse each module, we should restrict ourselves to modules that have high YALCOM/LCOM values.

JAVA code	LCOM1	LCOM2	LCOM3	LCOM4	LCOM5	YALCOM
class:FloatColumnType package:tech.tablesaw.columns.numbers `package tech.tablesaw.columns.numbers;` `/** The {@link ColumnType} for {@link FloatColumn} */` `public class FloatColumnType extends AbstractColumnType {` `  public static final int BYTE_SIZE = 4;` `  /** Returns the default parser for {@link FloatColumn} */` `  public static final FloatParser DEFAULT_PARSER = new FloatParser(ColumnType.FLOAT);` `  private static FloatColumnType INSTANCE;` `  private FloatColumnType(int byteSize, String name, String printerFriendlyName) {` `  super(byteSize, name, printerFriendlyName);` `  }` `  /** Returns the singleton instance of FloatColumnType */` `  public static FloatColumnType instance() {` `  if (INSTANCE == null) {` `  INSTANCE = new FloatColumnType(BYTE_SIZE, "FLOAT", "float");` `  }` `  return INSTANCE;` `  }` `  /** {@inheritDoc} */` `  @Override` `  public FloatColumn create(String name) {` `  return FloatColumn.create(name);` `  }` `  /** {@inheritDoc} */` `  @Override` `  public FloatParser customParser(ReadOptions options) {` `  return new FloatParser(this, options);` `  }` `  /** Returns true if the given value is the missing value indicator for this column type */` `  public static boolean valueIsMissing(float value) {` `  return Float.isNaN(value);` `  }` `  /** Returns the missing value indicator for this column type */` `  public static float missingValueIndicator() {` `  return Float.NaN;` `  }` `}`	15.0	0.0	6.0	6.0	1.07	1.0
class:DateAggregateFunction package:tech.tablesaw.aggregate	6.0	0.0	4.0	4.0	0.0	1.0

```
package tech.tablesaw.aggregate;
/** A partial implementation of aggregate functions to summarize over a date column */
public abstract class DateAggregateFunction extends AggregateFunction<DateColumn, LocalDate> {
  /**
   * Constructs a DateAggregateFunction with the given name. The name may be used to name a column
   * in the output when this function is used by {@link Summarizer}
   */
  public DateAggregateFunction(String name) {
    super(name);
  }
  /**
   * Returns an instance of LocalDate that is the result of applying this function to the given
   * column
   */
  public abstract LocalDate summarize(DateColumn column);
  /** {@inheritDoc} */
  @Override
  public boolean isCompatibleColumn(ColumnType type) {
    return type.equals(ColumnType.LOCAL_DATE);
  }
  /** {@inheritDoc} */
  @Override
  public ColumnType returnType() {
    return ColumnType.LOCAL_DATE;
  }
}
```

class:BooleanIntAggregateFunction package:tech.tablesaw.aggregate ``` package tech.tablesaw.aggregate; /** * A partial implementation of an AggregateFunction that returns an Integer value when applied to a * Boolean Column */ public abstract class BooleanIntAggregateFunction extends AggregateFunction<BooleanColumn, Integer> { /** * Constructs a BooleanCountFunction with the given name. The name may be used to name a column in * the output when this function is used by {@link Summarizer} */ public BooleanIntAggregateFunction(String functionName) { super(functionName); } /** Returns an Integer as a result of applying this function to the given column */ @Override public abstract Integer summarize(BooleanColumn column); /** {@inheritDoc} */ @Override public boolean isCompatibleColumn(ColumnType type) { return type.equals(ColumnType.BOOLEAN); } /** {@inheritDoc} */ @Override public ColumnType returnType() { return ColumnType.DOUBLE; } } ```	6.0	0.0	4.0	4.0	0.0	1.0
class:NumericAggregateFunction package:tech.tablesaw.aggregate	3.0	0.0	3.0	3.0	0.0	1.0

`` package tech.tablesaw.aggregate; /** A partial implementation of aggregate functions to summarize over a numeric column */ public abstract class NumericAggregateFunction extends AggregateFunction<NumericColumn<?>, Double> { /** * Constructs a NumericAggregateFunction with the given name. The name may be used to name a * column in the output when this function is used by {@link Summarizer} */ public NumericAggregateFunction(String name) { super(name); } /** {@inheritDoc} */ @Override public boolean isCompatibleColumn(ColumnType type) { return type.equals(ColumnType.DOUBLE) || type.equals(ColumnType.FLOAT) || type.equals(ColumnType.INTEGER) || type.equals(ColumnType.SHORT) || type.equals(ColumnType.LONG); } /** {@inheritDoc} */ @Override public ColumnType returnType() { return ColumnType.DOUBLE; } } ```						
class:TimeAggregateFunction package:tech.tablesaw.aggregate ``` package tech.tablesaw.aggregate; /** A partial implementation of aggregate functions to summarize over a time column */ public abstract class TimeAggregateFunction extends AggregateFunction<TimeColumn, LocalTime> { /** * Constructs a TimeAggregateFunction with the given name. The name is used as a column name in * the output */ public TimeAggregateFunction(String name) { super(name); } /** Returns a LocalTime object that is the result of applying this function to the given Column */ public abstract LocalTime summarize(TimeColumn column); /** {@inheritDoc} */ @Override public boolean isCompatibleColumn(ColumnType type) { return type.equals(ColumnType.LOCAL_TIME); } /** {@inheritDoc} */ @Override public ColumnType returnType() { return ColumnType.LOCAL_TIME; } } ```	6.0	0.0	4.0	4.0	0.0	1.0

Conclusion

This lab provided an in-depth analysis of software design by examining the cohesion and coupling of modules within real-world projects. By applying tools such as pydeps for dependency visualization and LCOM metrics for Java, the study uncovered several key insights:

- Cohesion and Coupling: The hierarchical approach to cohesion helps in understanding how well functions within a module work together. Meanwhile, the coupling analysis—ranging from data to content coupling—highlights the potential risks of shared code and global data,

emphasizing the need for careful modular design.

- Dependency Graph Analysis: The exploration of the Pandas dependency graph revealed significant cyclic dependencies. These cycles, particularly the extensive interdependencies in the main pandas module, indicate potential fragility, where changes in one module may propagate broadly across the system.
- Metrics for Impact Assessment: Using PageRank and instability metrics allowed for the ranking of modules based on their susceptibility to error propagation. The heat maps and effect matrices further demonstrated which modules are most critical, suggesting areas where design improvements could mitigate risks.
- Java Cohesion Analysis: The LCOM and YALCOM metrics applied to the Tablesaw project identified classes with high lack of cohesion. These classes are prime candidates for refactoring, which could lead to more maintainable and robust codebases.

Overall, the lab underscores the importance of balancing cohesion and coupling in software architecture. By carefully analyzing module interdependencies, developers can identify weak points in their designs, streamline code maintenance, and ultimately build more reliable systems.

Lab 10

Introduction

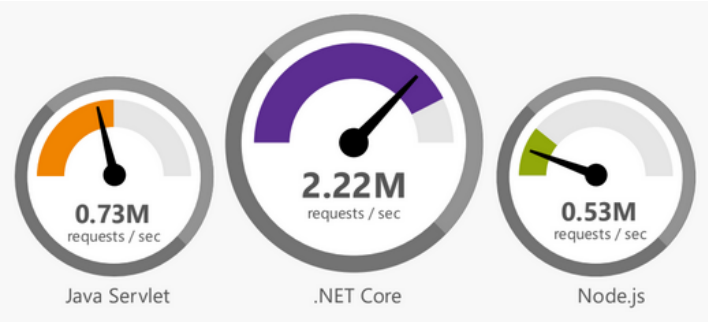
> `.NET` is a free and open-source application development platform supported by Microsoft.
> - Microsoft

The languages that use this framework are called `.NET` languages.
Just as C++ compiles to LLVM, the .NET languages compile to Common Intermediate Language (CIL). This is then translated to machine code by just-int-time (JIT) compilation.
Some popular `.NET` languages are :

- C# : similar to C/C++ and Java
- F# : This uses the functional programming paradigm
- Visual Basic : This is a rather "visual" language.

Note that "visual" means interactive, or event based.
While conventional programs have a unique and deterministic control flow graph, interactive programs use multithreading and multi-processing, and thus the output of the program is undecidable many times.
The inherent inclusion of threads and processes is needed because Event driven programming is supposed to be fast, asynchronous, and should fascilitate writing applications like video games and websites.
For example, front-end JavaScript code is usually event-driven as the browser needs it to be for optimal performance.
Similar to browsers, Integrated Development Environments (IDEs) like Visual Studio provide API to trigger and observe events inside the IDE itself.
When used with an IDE like Visual Studio to do event driven programming, C# is extended a bit (just as Arduino IDE extends C++ using its own libraries). This extended version is called Visual C#.

`.NET` is what is usually used to write GUI programs in Windows.
Since the `.NET` framework is used for event driven programming, of-course websites can also be writted using it. The version used for this task is called ASPNET.
ASPNET is what professional large websites such as RayGun, GoDaddy and Tencent are written in to ensure speed and reliability.
It is really fast, in fact around 20 times faster than `Node.js`.



Source : lecture slides

The goal of this lab is to get familiar with the most popular .NET language, namely C#, which is a modern, object oriented and type-safe language.
For this purpose, I have written several object oriented programs in C#, as dictated in this lab.

All this is done using Visual Studio, the most suitable IDE for `.NET` applications, on a Windows system.

Methodology

The rough timeline for work can be summarised by these steps :

1. Setting Up .NET Development Environment.
   - Open Visual Studio and create a new C# Console Application project.
   - Ensure the target framework is .NET 6 or later. (It was .NET 8 for my system)
   - Write a simple program (any) and run it just to test.
2. Understanding Basic Syntax and Control Structures
   Write an object-oriented C# programs that:

- Accepts user input for two numbers. This is done using `Console.ReadLine()` which return a string, that can be typecasted into integers explicitely using `Convert.ToInt32` or `Convert.ToInt64`
- Performs addition, subtraction, multiplication, and division.
- Uses if-else conditions to determine if the sum is even or odd. This is doable easily using the modulo (`%`) operator.
- Displays the results using `Console.WriteLine()`.

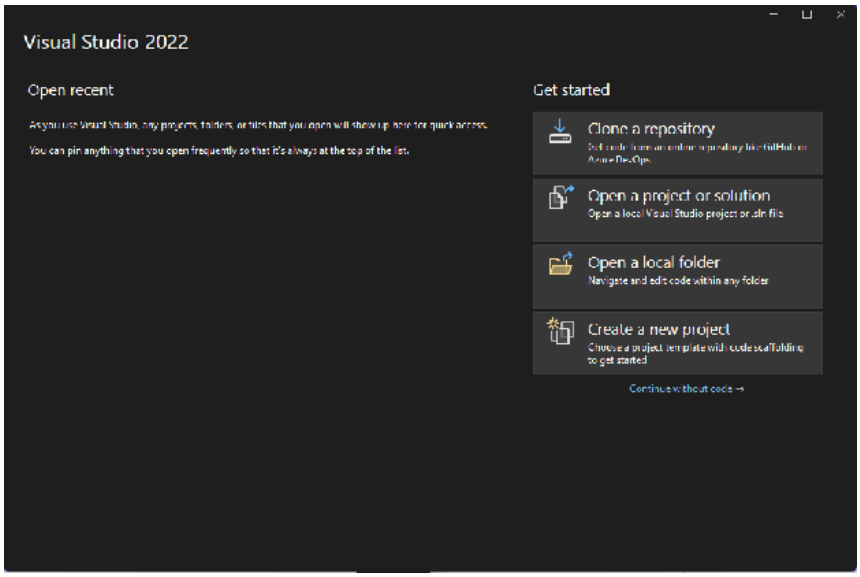
3. Implementing Loops and Functions

   Design an object-oriented C# program that:
   - Uses a for loop to print numbers from 1 to 10.
   - Uses a while loop to keep asking the user for input until they enter "exit".
   - Defines and calls a function that calculates the factorial of a number provided by the user. This can be done by defining a local variable with the value of the function, inside the `Main` method. There's no need for adding a global function.
4. Perform Object-Oriented Programming in C#
   - Create a class Student with:
     - Properties: `Name`, `ID`, `Marks`. We can keep the `Marks` attribute to be private.
     - A constructor to initialize these values. In C#, the constructor is the method with the same name as the class. It doesn't return anything explicitely. If not defined, the defailt constructor is called.
     - A method `getGrade()` that returns the grade based on marks ('A', 'B', 'C', etc.).
     - A `Main()` method to create and display student details.
   - Create a sub-class StudentIITGN from Student with:
     - A new property: `Hostel_Name_IITGN`
     - A `Main()` method to create and display IITGN student details. This can be done by first calling the `Main` from the base class and then print more details.
5. Exception Handling
   - Modify the program from Activity 2 to handle exceptions:
   - Use try-catch to handle division-by-zero errors.
   - Ensure the program does not crash on invalid input.
6. Debugging using Visual Studio Debugger
   - For Activities (2) to (5), visually illustrate6 program execution in Debug mode by inserting breakpoints at appropriate places.
   - Your illustration should cover operations: step-in, step-over, step-out.

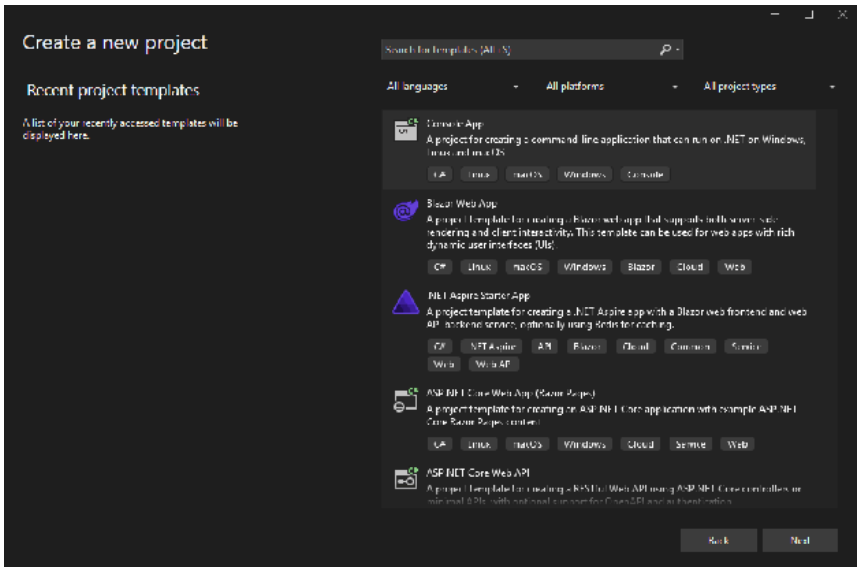
Results

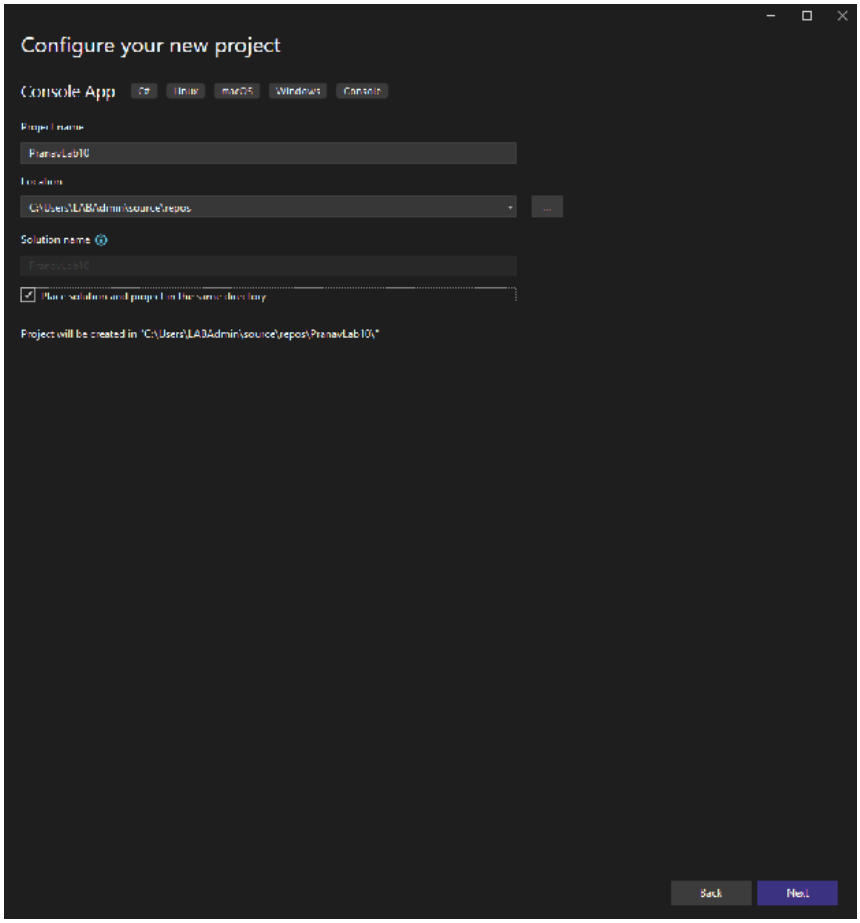
Setting up .NET development Environment

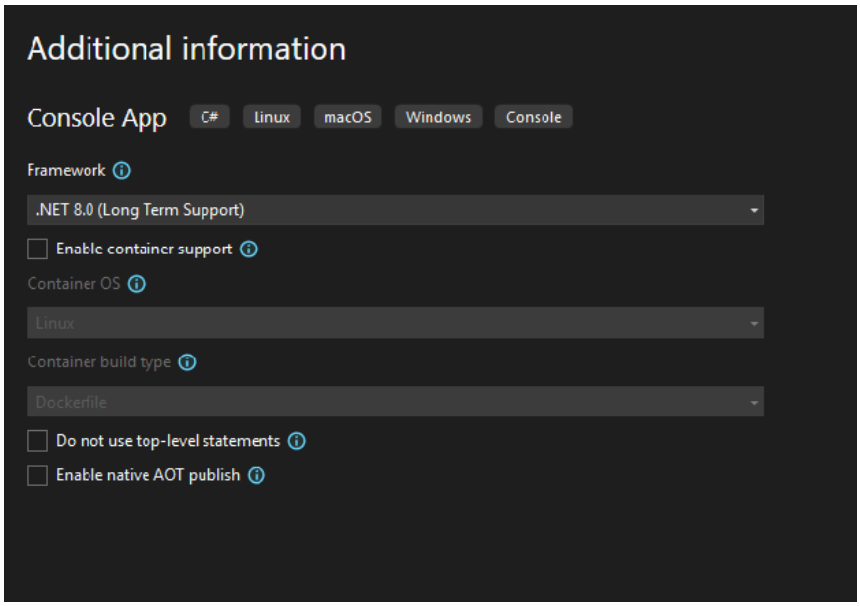
1. Opening Visual Studio (VS)

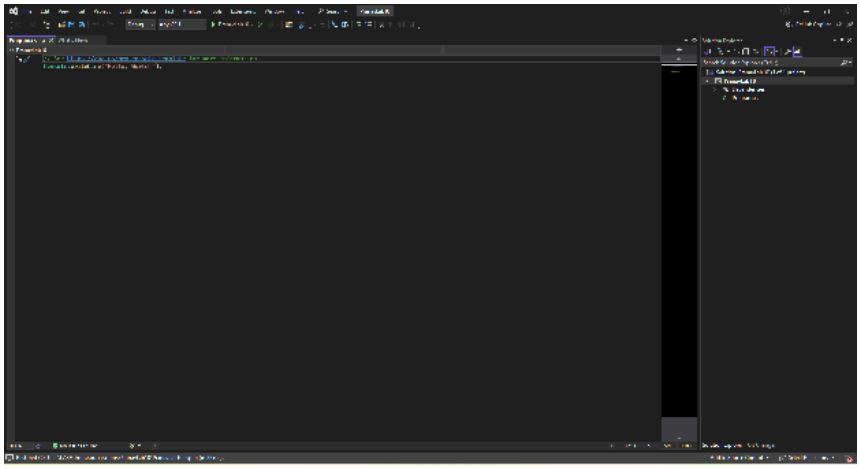


2. Creating a C# console application


Create a new project
Recent project templates
A list of your recently accessed templates will be displayed here.
All languages
All platforms
All project types
Console App
Blazor Web App
.NET Aspire Starter App
ASP.NET Core Web App (Razor Pages)
ASP.NET Core Web API
Back
Next

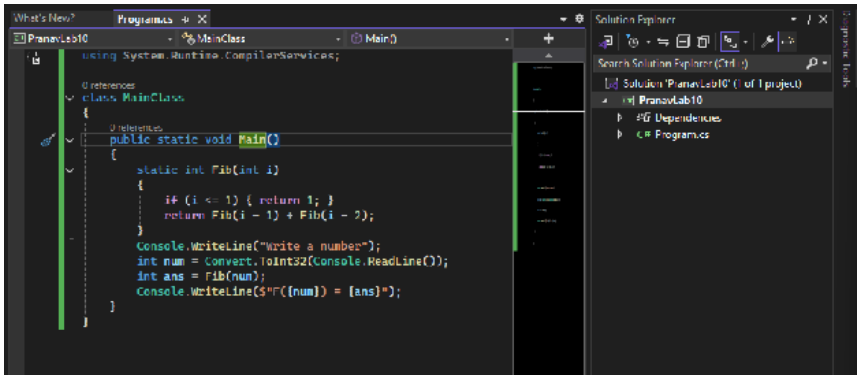

Configure your new project
Console App
C#
Linux
macOS
Windows
Console
Project name
PranavLab10
Location
C:\Users\LAB\Admin\source\repos\
Solution name
Place solution and project in the same directory
Project will be created in "C:\Users\LAB\Admin\source\repos\PranavLab10\"
Back
Next



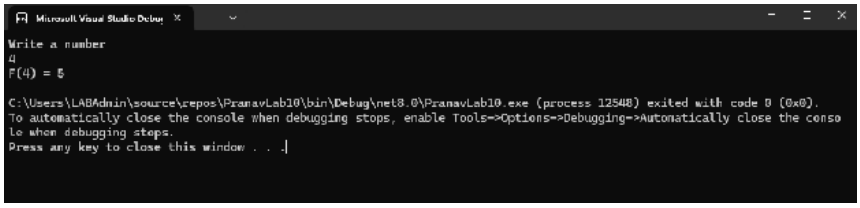


The target framework is .NET 8.0

3. Writing a simple Fibonacci number calculation program



4. Running it



Basic control flow

I wrote this program that takes in 2 numbers as input and uses control flow to decide if sum is even or odd. It also prints the sum,product,quotient and difference.

```
using System.Runtime.CompilerServices;

0 references
class MainClass
{
    0 references
    public static void Main()
    {
        int x, y, xpy,xmy,xty,xdy,so;
        Console.WriteLine("Write a number");
        x = Convert.ToInt32(Console.ReadLine());
        Console.WriteLine("Write another number");
        y = Convert.ToInt32(Console.ReadLine());
        xpy = x +y;
        xmy = x - y;
        xdy = x / y;
        xty = x * y;
        so = xpy % 2;
        Console.WriteLine($"sum : {xpy}");
        Console.WriteLine($"difference : {xmy}");
        Console.WriteLine($"product : {xty}");
        Console.WriteLine($"quotient : {xdy}");
        if (so == 1)
        {
            Console.WriteLine("sum is odd");
        }
        else
        {
            Console.WriteLine("sum is even");
        }
    }
}
```

Running it :

```
Write a number
24
Write another number
4
sum : 28
difference : 20
product : 96
quotient : 6
sum is even

C:\Users\LABAdmin\source\repos\PranavLab10\bin\Debug\net8.0\PranavLab10.exe (process 19752) exited with code 0 (0x0).
To automatically close the console when debugging stops, enable Tools->Options->Debugging->Automatically close the conso
le when debugging stops.
Press any key to close this window . . .
```

Loops and functions

Since the bullet points given for this section are so unrelated, I'll write separate programs, rather than writing a single program for an unlikely amalgamation of these tasks.

1. A program to print numbers from 1 to 10 using a `for` loop

```
using System.Runtime.CompilerServices;

0 references
class MainClass
{
    0 references
    public static void Main()
    {
        // program that prints numbers from 1 to 10
        for(int x = 1; x <= 10; x ++)
        {
            Console.WriteLine(x);
        }
    }
}
```

   Running this :

```
1
2
3
4
5
6
7
8
9
10

C:\Users\LABAdmin\source\repos\PranavLab10\bin\Debug\net8.0\PranavLab10.exe (process 27068) exited with code 0 (0x0).
To automatically close the console when debugging stops, enable Tools->Options->Debugging->Automatically close the conso
le when debugging stops.
Press any key to close this window . . .
```

2. A program that asks users to enter text till the use enters exit using a `while` loop :

```
PranavLab10                    MainClass                    Main()
using System.Runtime.CompilerServices;

0 references
class MainClass
{
    0 references
    public static void Main()
    {
        string s="keep running";
        while (s !="exit")
        {
            Console.WriteLine("Enter some text.. type \"exit\" to exit.");
            s = Console.ReadLine();
        }
        Console.WriteLine("bye!");

    }
}
```

```
Enter some text.. type "exit" to exit.
hi
Enter some text.. type "exit" to exit.
hello
Enter some text.. type "exit" to exit.
how is it going ?
Enter some text.. type "exit" to exit.
I'm lonely .. :(
Enter some text.. type "exit" to exit.
Why are you like this ?
Enter some text.. type "exit" to exit.
I want to eat a sandwich..
Enter some text.. type "exit" to exit.
exit
bye!

C:\Users\LABAdmin\source\repos\PranavLab10\bin\Debug\net8.0\PranavLab10.exe (process 27416) exited with code 0 (0x0).
To automatically close the console when debugging stops, enable Tools->Options->Debugging->Automatically close the conso
le when debugging stops.
Press any key to close this window . . .
```

3. A program that calculates the factorial of a number using a function :

```
0 references
class MainClass
{
    0 references
    public static void Main()
    {
        void F()
        {
            Console.WriteLine("Enter a number:");
            int x = Convert.ToInt32( Console.ReadLine() );
            int f = 1;
            for(int y = 2; y <= x; y++)
            {
                f = f * y;
            }
            Console.WriteLine($"{x}! = {f}");
        }
        F();
    }
}
```

```
Enter a number:
5
5! = 120

C:\Users\LABAdmin\source\repos\PranavLab10\bin\Debug\net8.0\PranavLab10.exe (process 16996) exited with code 0 (0x0).
To automatically close the console when debugging stops, enable Tools->Options->Debugging->Automatically close the conso
le when debugging stops.
Press any key to close this window . . .
```

Object Oriented Programming

1. Making a `Student` class

```
3 references
class Student
{
    public int Id;
    public string Name;
    public int Marks;

    1 reference
    public Student()
    {
        Id = 0;
        Name = "unk";
        Marks = 0;
    }

    1 reference
    public string getGrade()
    {
        if (Marks == 0) return "F";
        else if (Marks <= 50) return "C";
        else if (Marks <= 80) return "B";
        else if (Marks <= 100) return "A";
        else return "Error";
    }

    1 reference
    public void Main(int Idval, string Nameval, int Marksval)
    {
        this.Id = Idval;
        this.Name = Nameval;
        this.Marks = Marksval;
        Console.WriteLine($"name : {this.Name}");
        Console.WriteLine($"Id : {this.Id}");
        Console.WriteLine($"grade : {getGrade()}");
    }

}
```

2. Creating a subclass `StudentIITGN` :

```
3 references
class StudentIITGN : Student
{
    public string Hostel_Name_IITGN;
    1 reference
    public StudentIITGN() : base() {
        Hostel_Name_IITGN = "unk";
    }

    1 reference
    public void Main(int Idval, string Nameval, int Marksval, string Hostel)
    {
        Console.WriteLine($"IITGN student {Id} :");
        base.Main(Idval,Nameval,Marksval);
        this.Hostel_Name_IITGN= Hostel;
        Console.WriteLine($"Hostel : {Hostel_Name_IITGN}");
    }

}
```

Exception handling and step-wise execution

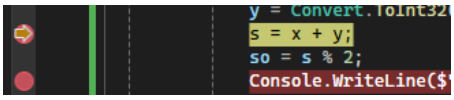
Consider this modified version of the code from section 2:

```
0 references
class MainClass
{
    0 references
    public static void Main()
    {
        int x, y, s, so;
        Console.WriteLine("Write a number");
        x = Convert.ToInt32(Console.ReadLine());
        Console.WriteLine("write another number");
        y = Convert.ToInt32(Console.ReadLine());
        s = x + y;
        so = s % 2;
        Console.WriteLine($"sum : {s}");
        Console.WriteLine($"difference : {x - y}");
        Console.WriteLine($"product : {x * y}");
        try { Console.WriteLine($"quotient : {x / y}"); }
        catch { Console.WriteLine("division by zero not allowed"); }
        if (so == 0) Console.WriteLine("sum is even");
        else Console.WriteLine("sum is odd");
        }
    }
```

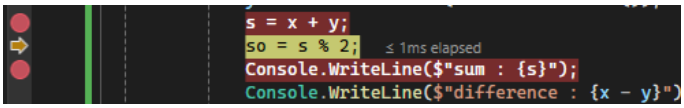
The red dots are break points.

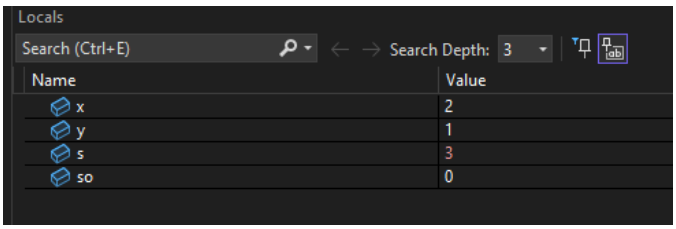
It runs like this :

```
Write a number
2
write another number
1
```



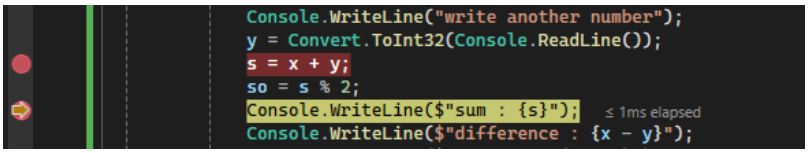
After stepping into highlighted line :



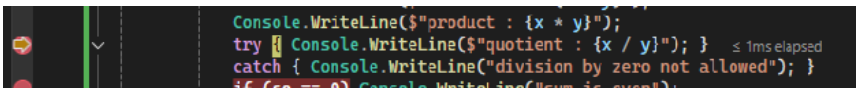


Continuing …

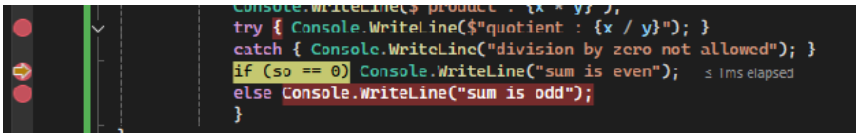
```
Write a number
2
write another number
1
```

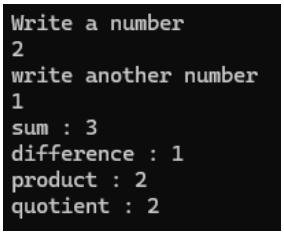


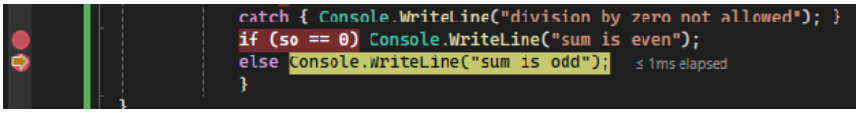

```
Write a number
2
write another number
1
sum : 3
difference : 1
product : 2
```

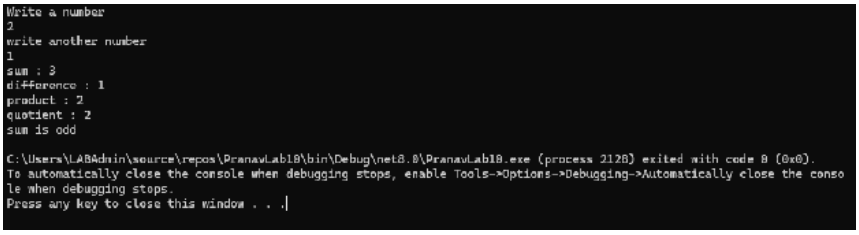



```
Write a number
2
write another number
1
sum : 3
difference : 1
product : 2
quotient : 2
```









Notice that since there is no invocation of methods from the same file, thus there is no noticeable difference between stepping into, over, or out.

Extra Questions

Copy Constructor and Overloading Constructors in C++

A copy constructor is a special constructor in C++ that initializes a new object by copying an existing object's members. It is invoked when:

- An object is initialized from another object of the same class.
- An object is passed by value to a function.
- An object is returned by value from a function.

Syntax:

```
class ClassName {
public:
    ClassName(const ClassName &obj) {
        // Copy attributes from obj to the current object
    }
};
```

For example:

```
class MyClass {
public:
    int value;
    MyClass(int val) : value(val) {}
    MyClass(const MyClass &obj) { value = obj.value; }
};

int main() {
    MyClass obj1(10);
    MyClass obj2 = obj1; // Copy constructor invoked
    return 0;
}
```

The copy constructor can be customized for deep copying if the class contains dynamically allocated resources.

Constructor Overloading:

Constructor overloading allows multiple constructors in the same class, differentiated by the number or type of parameters. For example:

```
class Area {
public:
    int area;
    Area() { area = 0; } // Default constructor
    Area(int side) { area = side * side; } // Constructor with one parameter
    Area(int length, int width) { area = length * width; } // Constructor with two parameters
};
```

Overloaded constructors can be invoked based on the arguments provided during object creation

Why Does `Main()` Need to Be Static?

The `Main()` method in languages like C# and Java is static because it serves as the program's entry point. Being static ensures that it can be called without creating an instance of the class. This is essential because no objects are instantiated when the program starts.

What Happens If `Main()` Calls Itself?

If `Main()` calls itself recursively, it will result in a stack overflow error because each call adds a new frame to the call stack, which eventually exceeds its limit.

What Happens If `Main()` Is Spelled as `main()`?

In C#, renaming `Main()` to `main()` will cause a compilation error because the runtime looks specifically for a method named Main with the correct signature (`public static void Main(string[] args)`)
. In Java, naming conventions also require main to be lowercase, and any deviation will prevent the program from running.

What Happens When Both Base-Class and Derived-Class Have Their Own Main() Methods?

If both a base class and a derived class define their own static `Main()` methods, only one of them will act as the program's entry point, depending on which class is specified as the startup object during compilation or execution. For example:

```
class Base {
    public static void Main(string[] args) {
        Console.WriteLine("Base Main");
    }
}

class Derived : Base {
    public static void Main(string[] args) {
        Console.WriteLine("Derived Main");
    }
}
```

If you run this program with Derived as the entry point, it will execute `Derived.Main()`. The base class's `Main()` method will not be executed unless explicitly called.

Conclusion

Throughout this lab, I gained a deeper understanding of how C# supports a wide range of applications, as noted in the introduction. I set up my development environment in Visual Studio and worked on programs that ranged from simple arithmetic operations to more complex control flows and object-oriented designs. This hands-on experience helped me see how C# effectively supports both GUI and web applications through its event-driven model.

By exploring loops, functions, and exception handling, I observed how the language’s clear syntax and structure simplify managing complex operations and reduce errors during debugging. The emphasis on classes, constructors, and methods further enabled me to build modular, reusable code that is essential for large-scale projects.

Visual Studio significantly enhanced my learning experience by providing a robust, intuitive platform. Features like breakpoints and step execution streamlined the debugging process and clarified the program’s flow, allowing me to focus more on coding and problem-solving.

Overall, this lab has been a valuable exercise in understanding how C# and Visual Studio work together to create fast, interactive, and reliable applications.