Programming 11 - Final Homework

There is an FAQ section at the end of this assignment based on past semester's questions. Check it out and feel free to ask questions yourself.

This assignment is in 3 parts and all are related, building off one another. So instead of submitting 3 separate PDFs, you'll submit a single memo that contains all the pseudocode/flowcharts, code, figures and responses to the prompts.

Introduction

As an engineer, you may be required to make measurements of physical quantities such as weight, volume and temperature. In most instances little thought is required in selecting an appropriate instrument to accomplish the measurement. However, when the stakes are high and a considerable amount of money is on the line, the selection of measurement equipment and the techniques used in the interpretation of data can demand considerable attention.

The objective of any measurement system is to determine the best estimate for the true value of a physical quantity. This estimation is based on the tendencies of the measurement device though. In order to better understand how a measurement system will respond to a particular form of input, an engineer will use numerical modeling.

A simple example of the dynamic nature of a measurement system is to consider using a bulb thermometer to measure body temperature. The thermometer initially at room temperature is placed under the tongue. Even after a few seconds the thermometer will not measure the expected value of the body. Watching the display we can see that the thermometer’s temperature is constantly changing. But the body temperature is a constant! We all know that if we wait long enough we will in fact measure the correct body temperature. We have to wait because there is an energy storage element that requires a finite amount of time to respond to the step input change in temperature. Not understanding this could lead to false conclusions about the measurement and the condition of your health.

Final Project:

Your final project is to perform a numerical analysis of a temperature sensing device called a thermocouple which is to be used as one component in a measurement system. A thermocouple is fabricated by joining two dissimilar metal wires at each end. Thomas Seebeck (1770 -1831) was the first to discover that if the temperatures of the two junctions where the wires are joined are not the same, then a small voltage will be produced across the junction (Fig. 1).

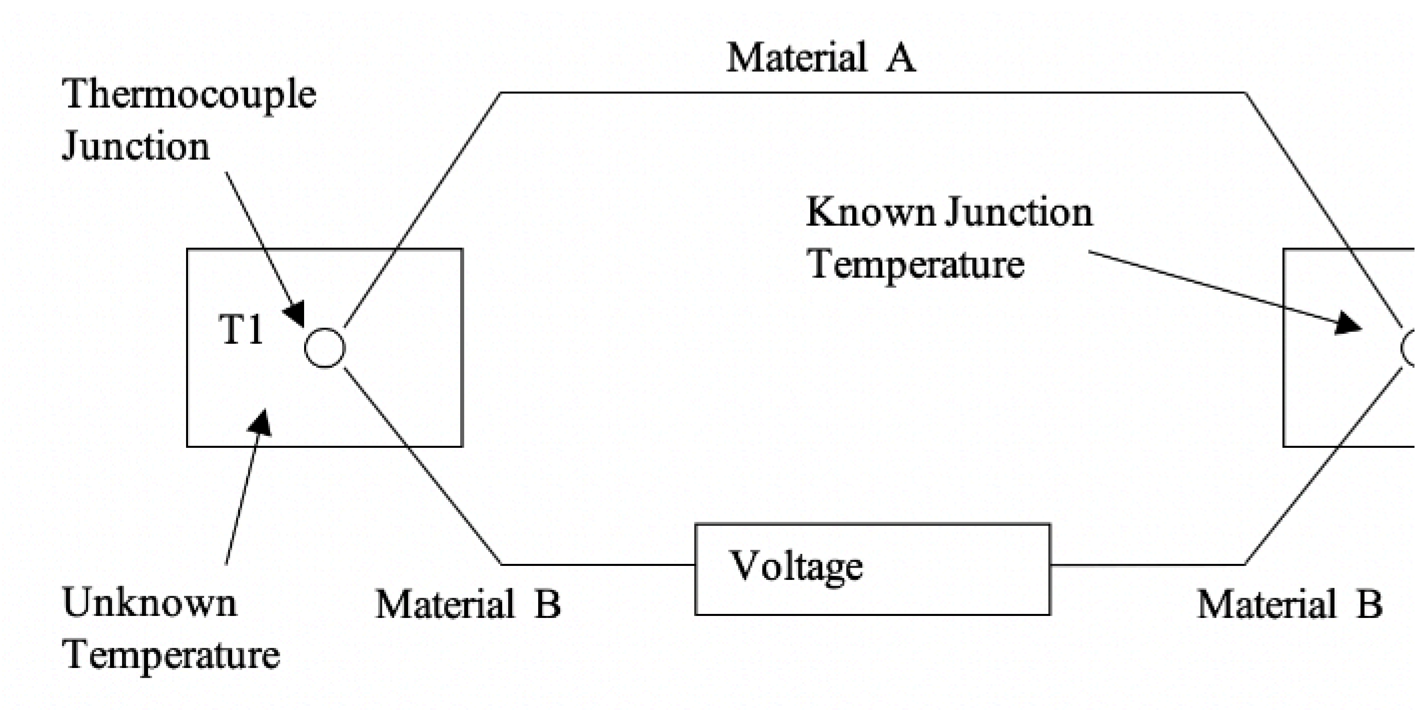

Fig 1. Basic Thermocouple Circuit showing two dissimilar metals with junctions at temperatures T1 and

In order to make a temperature measurement with a thermocouple one has to measure the voltage across the two junctions and know the temperature of one of the junctions. The thermocouple is usually connected to a computer by means of an analog to digital converter to create a data acquisition system. Your task is to model a series of possible thermocouple designs to see which one will best fit your data acquisition system's requirements for transducer measurement response time.

The Model:

A simple, yet common, transient heat conduction problem is one in which a solid experiences a sudden temperature change in its thermal environment. We will consider the thermocouple junction to be a solid in the shape of a sphere (See Fig 2).

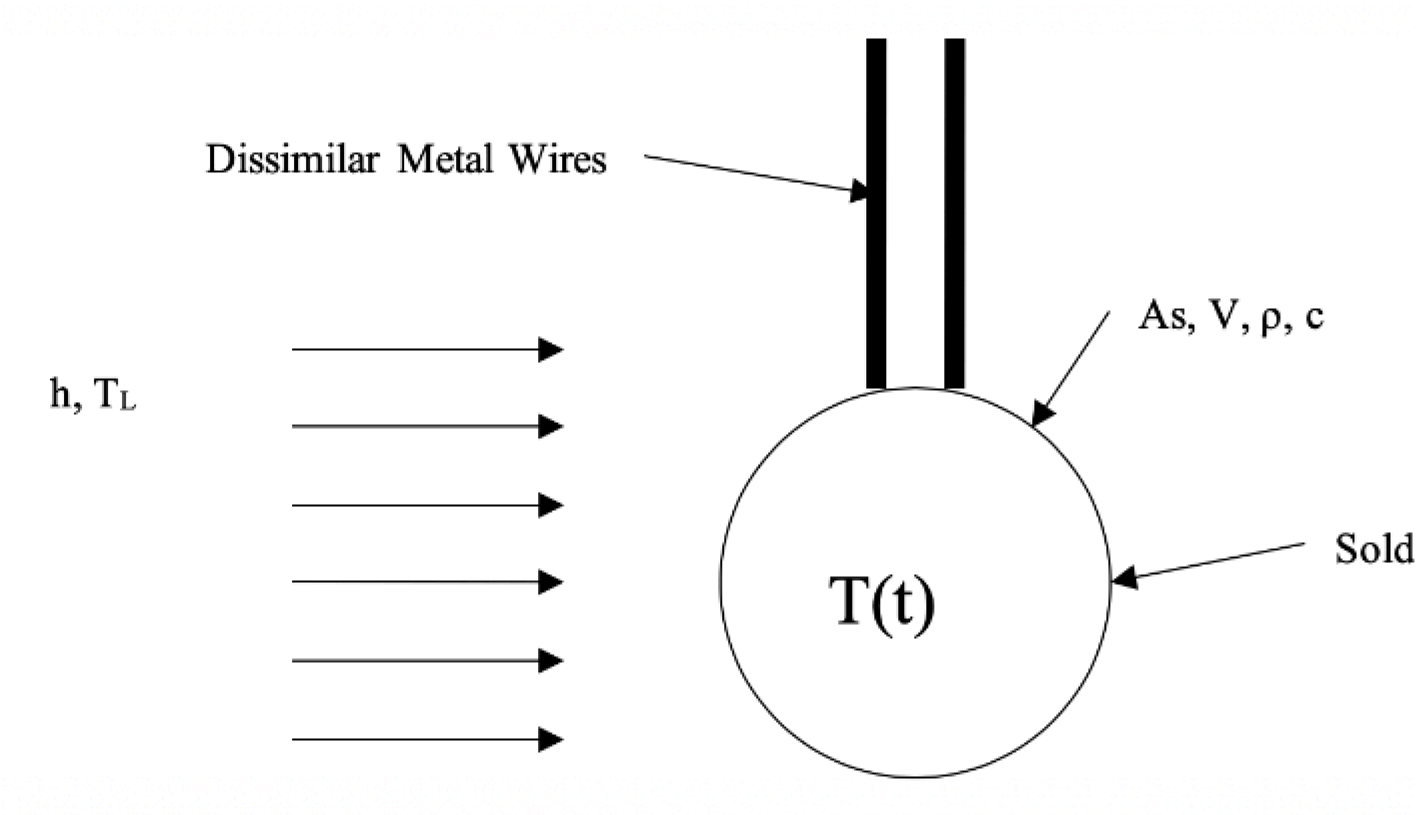

Fig 2. Thermocouple Junction modeled as a sphere.

The junctions are formed by twisting the wire ends then applying a bead of solder to create a weld. The thermocouple junction (sphere) is initially at a uniform temperature T_o and is then immersed in a liquid of lower temperature T_L. If the process begins at time $t = 0$, the temperature of the thermocouple will decrease for time $t > 0$ until it eventually reaches the liquid temperature T_L. The equation for the rate of change of the thermocouple junction temperature is:

$$rate\_of\_change(\frac{T}{t}) = \frac{hA_s(T_L - T)}{mc}$$

Where:

- T = *Thermocouple junction temperature at current time (sphere)()*
- T_L = *Liquid temperature ()*
- h = *heat transfer coefficient ()*
- A_s = *sphere surface area(* m^2*)* = $4\pi r^2$
- m = *sphere mass ()* = $\rho * v$
- c = *sphere specific heat ()*

- ρ= *density of sphere ()*
- v = *sphere volume* (m^3) = $\frac{4}{3}\pi r^3$
- r = sphere radius

The rate of heat loss is not constant! It depends on the temperature difference between the thermocouple junction (sphere) and the liquid and their thermal physical properties. As that changes, the rate of heat loss changes.

To produce the temperature history we can apply equation 1 in very small increments of time called a ***time step(*** $\triangle t$ ***)***. Starting from time equal to zero your program will have the following logic:

Program Steps:

Step 1: Read in the values of T_L , T_o, h , ρ, c, r and Δt.

Step 2: Call a function called `rate_of_change(...)` that will return the rate of change given the input parameters as defined in equation 1. Remember that the sphere temperature T changes with every time step. You will start at time equal to zero with the sphere temperature equal to T_o.

Step 3: Find the new temperature knowing the temperature at the beginning of the time step (old temp) and the ***change in temperature*** (ΔT_i) due to ***rate of change***($\frac{T_i}{t_i}$) at any given **step**(i). The equations are:

$$\begin{aligned} \Delta T_i &= \Delta t * (\tfrac{T_{i-1}}{t_{i-1}}) \\ T_i &= T_{i-1} + \Delta T_i \end{aligned}$$

Use $\triangle t$ =0.001 seconds.

NOTE: If this gives you an overflow error due to memory load or some other computer limitation, you may use a maximum of 0.01 seconds but try for the smallest time step your computer can handle. Try switching to using doubles first before going for the larger timestep though.

Step 4: Proceed to the next time step and repeat step 3. The next time is given as:

$t_i = t_{i-1} + \Delta t$

Step 5: Apply these equations until the value of the sphere temperature reaches within 0.1 degrees of the liquid temperature T_L. Your program should then stop printing out the temperature history.

Example Output

This is a simplified program test case for your program, not an example of a properly formatted output for this assignment. Your output values may differ slightly depending on your timestep, order of calculations, and other factors. Also, I just typed it with small offsets in the Temp numbers instead of copy-pasting the result from my answer key so you **MUST** go by your calculations and not aim for this specific example output.

```
Enter initial temperature of thermocouple junction (sphere) (C) : 100
Enter liquid temperature (C) : 25
Enter heat transfer coefficient (W/m2K) : 1000
Enter sphere density (kg/m3) : 8922
Enter sphere specific heat (J/kgK) : 287
Enter sphere radius (m) : 0.0005
Enter desired time step for temperature history (s) : .001

Output:
Time (s) Temp (C)
0.0000   100.0000
0.0010   99.8243
0.0020   99.6489
0.0030   99.4740
0.0040   99.2995
. . .
2.8200   25.1005
2.8210   25.1002
2.8220   25.0999

time to steady state temperature: 2.8220 Seconds
```

The Analysis:

It is clear from the above equations that the rate of change of temperature (system response) is affected by the heat transfer coefficient (h), size of the junction (A_s and v) and the type of materials used (ρ and c). The heat transfer coefficient (h) is a function of the problem geometry and the thermo-physical properties of the materials involved. The size of the solder bead will effect the response time and the strength of the junction. From the above equation one sees that to decrease the response time the radius should be decreased. However, a small radius will result in possible failure of the junction in extreme environments. The last parameter to consider is the energy storage element of the junction. This is the product of density, volume and specific heat. The higher the value the longer it will take the thermocouple to respond to a temperature change.

Assignment:

Part 1 - Development of the Algorithm

Develop a **C++** program based on the model described above. **You are required to use at least the one function previously mentioned.** Your program should prompt the user for the values of the heat transfer coefficient, density, specific heat, time step, initial temperature of the junction, the liquid temperature, and the sphere radii you would like to test. It should write the temperature / time history to a file. Using arrays to organize this information can help when converting this for Part 2 and 3 but is not required. **Benchmark (test) your program against the example provided above to verify it works!** This C++ program is to just **output the data to a file**. You should be using the console output to monitor the program but what's required is that data output. You will load that data into MATLAB to create a visual representations for reporting the data out in the memo.

Plot the transient response curve, temperature vs time, of the test case in **MatLab** and include these results as an attachment to your memo.

Assignment Note: You do not need to submit the Matlab code BUT there's going to be a few plots. You'll want to create an .m file to make this step more repeatable rather than going through command window prompts.

Answer the following questions in your memo:

- Is the response of the thermocouple junction linear?
- If not what does the response look like? Why?

Part 2 - Test Cases

We are interested in determining how the thermocouple response time is affected by the size and material used in the junction weld. There are two types of weld material that will be considered. The thermo-physical properties are given in the table below. The **minimum weld size radius is 0.3mm**, based on the wire gage used. The **minimum heat transfer coefficient** expected for the experiment is **1200 W/m2K**. The **temperature is expected to vary** between **30 and 120 C**.

Material	Specific Heat (J/kgK)	Density (kg/m^3)
Tin/Lead (60/40)	287	8922
Tin/Lead (56/44)	260	8700
Tin/Lead (50/50)	178	9325
Tin/Lead (43/57)	190	9400

The data acquisition system records a reading every 5 seconds. This means that the thermocouple must have a response time less than 5 s or it will not give accurate results. Determine the maximum radius of the junction weld for each material by modifying your program to see how long it takes for each thermocouple to respond to within 0.1 degrees of the final steady state temperature. Start at the minimum weld radius and increase in steps of 0.05 mm until the maximum time limit is exceeded. Use a time step of .01 seconds.

Plot weld radius verses time to steady state temperature for all materials on the same figure. You should be able to determine the maximum size of the weld radius from this plot.

Plot the transient response curves(temperature vs time) for the minimum radius(0.3 mm), the maximum radius and the middle radius value for each material. You may either create one plot per material or plot them all on the same figure, whichever you determine best illustrates the distinctions between them for your arguments in the memo.

Answer the following questions in your memo:

- Which material has the fastest response time?
- If a higher Tin content slightly increases strength but a higher Lead content greatly decreases cost, which material should we use? The thermocouple will be part of an engine safety monitoring system on of several makes and models of common commercial vehicles.

Part 3 - Examine the Data Acquisition System

We would now like to investigate the effect of the heat transfer coefficient on the data acquisition system. For the following run **use the input data of the benchmark test case (From Part 1)**.

Modify your program so that the heat transfer coefficient varies from a minimum value of 300 W/m^2K to 1000 W/m^2K in increments of 25 W/m^2K.

Plot the value of the heat transfer coefficient verse the time it takes to reach the steady state temperature for this case.

Answer the following questions in your memo:

- What is the shape of this curve and why?
- What is the minimum recommended value of the heat transfer coefficient that could be used for the benchmark test case with the current data acquisition system?
- How long should you wait to take a measurement if the heat transfer coefficient is 300 W/m^2K? How long if it is 750 W/m^2K?

Assignment Time Show Responses

How long, in minutes, did this assignment take you? If you complete this outside of class time, still include the 100 min alotted for this in class.

No correct answer has been set for this question

Submission Requirements:

- A memo or business style letter, addressed to me (Prof. B. O'Connell, First Year Engineering, Northeastern University, Boston, MA 02115), summarizing the results of all plots and answers to all questions.
  - Named: `P11H'First initial''First 4 letters of last name'.pdf`
    - Submit as a single PDF
  - Appropriate form, grammar, spelling, and clear writing as well as content will be grading criteria.
  - **To be included as attachments/appendices:**
    - All Matlab plots with appropriate titles and labels

            - **Do not use screengrabs!** Use **Save As** or the `saveas(...)` command to create an image from a figure.
        - All **flowcharts or pseudocodes** for all 3 parts
        - All **Sourcecode** for all 3 parts
            - This is so I can review it relatively quickly in a single document. I would still like the raw source code files (required below) so that I can run them if necessary.
- All source code files
    - `P11H1_'First initial''First 4 letters of last name'.cpp`
    - `P11H2_'First initial''First 4 letters of last name'.cpp`
    - `P11H3_'First initial''First 4 letters of last name'.cpp`
    - If applicable:
        - `P11H1_'First initial''First 4 letters of last name'.m`
        - `P11H2_'First initial''First 4 letters of last name'.m`
        - `P11H3_'First initial''First 4 letters of last name'.m`

Rubric

Memo

35% Total

- **Main body**
    - Appropriate form, grammar, spelling, and clear writing
    - All questions answered
    - Uses data appropriately to support responses
- **Attachments/Appendices**
    - All figures/plots included and properly formatted
    - All Pseudocode/flowcharts included and **not** produced by hand
    - All source code included

P1: Development of the Algorithm

25% Total

- **Pseudo-Code / Flowchart**
    - Logical approach to issue
    - Well written/Communicated
- **Code**

    - Includes header with description
    - Includes intro and user instruction
    - Commented throughout and cleanly
    - Runs without errors
    - Appropriate/required Commands/Functions
    - Performs as required

P2: Test Cases

20% Total

- **Pseudo-Code / Flowchart**
    - Logical approach to issue
    - Well written/Communicated
- **Code**
    - Includes header with description
    - Includes intro and user instruction
    - Commented throughout and cleanly
    - Runs without errors
    - Appropriate/required Commands/Functions
    - Performs as required

P3: Examine the Data Acquisition

20% Total

- **Pseudo-Code / Flowchart**
    - Logical approach to issue
    - Well written/Communicated
- **Code**
    - Includes header with description
    - Includes intro and user instruction
    - Commented throughout and cleanly
    - Runs without errors
    - Appropriate/required Commands/Functions
    - Performs as required

Frequently Asked Questions

How do I get C++ and MATLAB to work together?

You don't. It can be done, but you don't need too. There are MATLAB commands for calling a .cpp file and running as well as ways in C++ to trigger a MATLAB script to run, but we're not going that deep into things.

We're going to focus on how you'll more realistically use these tools, or ones like them, in the next few years. You're doing the work in C++ and then do all the graphical representations in MATLAB. You don't need to write a full MATLAB program for the plotting aspect and submit it. It's not a bad idea to write a short program for yourself though since you'll have to do several plots that need to be formatted well for communication. Just running the plot command won't get you there so why retype out everything every time.

Why do we need to use both if we could just do it in MATLAB?

This is something you could calculate and do in MATLAB. It's even similar to things we have done in MATLAB, **BUT...**

It's not uncommon to run data in one application and use another for representation. For instance, when I develop web apps or database systems I use postgresql for data handling and python/django for application and UI. For large data processing centers where you want to run an analysis on their server that's going to be computationally heavy, you would typically write an application in C++ and have it output data files periodically for you to view and work with in systems like MATLAB that's better for visualizations. C++ is more robust allowing you far more flexibility in your analysis but MATLAB is far easier to quickly visualize data. You're not at a phase where your analysis needs go beyond MATLAB's capabilities though so we're arbitrarily forcing you to for this assignment.

I'm not achieving steady state. What's wrong?

Deal with one variable changing at a time, not simultaneously.

Do I need to write and submit MATLAB scripts for Plotting?

No but I doubt you're not going to be outputting 1 two column text file and then plotting it, you're going to be making several. A script would save you some time. If you do write one, include it in your memo and include the m-file in your submission.

I will answer more questions here as they come up or I recall them.

I'm having an issue with my code...

Send me your code and screen grab any errors. Don't just send a request for help or vague description of the issue. I want you to succeed and want to help you do so but you have to help me to help you by providing me all of the information.