AME 535a: Introduction to Computational Fluid Dynamics

University of Southern California **Fall 2022**

Course Syllabus

Logistics

Term Fall 2022 (Aug 22 – Dec 14, 2022)

Lectures Tuesdays and Thursdays, 2 – 3:20pm Pacific Time

In OHE 100C and on DEN@Viterbi

Instructor Dr. Saakar Byahut Email: byahut@usc.edu
Office hours: Tue/Thu 4 – 6pm in OHE 500N and over Zoom:
https://usc.zoom.us/j/91659439804?pwd=cjhsVFNXYkVNSlkzOFlGZkROdjdzUT09

TA/Grader Tianbo (Raye) Xie Email: tianboxi@usc.edu
Office hours: Mon 2 – 4 pm / Wed 10am – 12pm in VHE 202 and over Zoom:
https://usc.zoom.us/j/91411223684?pwd=azJldHdIdmFCWnB3eFE3aytDZm5SZz09

IT Help https://viterbigrad.usc.edu/technical-support/
Email: dentsc@usc.edu Phone: 213-740-9356

The most efficient way to communicate with the instructor or the TA is via Piazza or Slack.
If you reach out via email, please use your USC email account and allow 2–3 days to receive a reply.

Course Description

The goal of the course is to teach fundamental techniques most commonly used to solve partial differential equations (PDEs) numerically, with particular focus on the equations governing fluid flows. Finite difference, finite volume, and finite element methods are studied as different means of discretizing a multitude of equations central to applications in science and engineering. A theoretical background on accuracy, consistency, stability, and convergence of the numerical schemes is provided, as well as both direct and iterative solution techniques for discrete linear systems.

Learning Objectives

After completing the course, you will be able to:

- Describe the major characteristics and general formulations of the three classes of numerical methods studied: finite differences (FD), finite volumes (FV), finite elements (FE)
- Understand and demonstrate the "well-posedness" of numerical methods for PDEs, including being able to prove consistency, stability, and convergence
- Derive and implement schemes for linear and non-linear PDEs, with and without time dependence, and prove their convergence and order of accuracy
- Define and implement Dirichlet- and Neumann-type boundary conditions in a manner consistent with the numerical scheme
- Explain common issues arising during implementation of numerical schemes on finite-precision computers, and acquire basic good-practice coding habits
- Use iterative techniques to effectively solve systems of linear equations encountered after spatial discretization of PDEs

Recommended Preparation

- AME 526 Engineering Analytical Methods (or equivalent course in partial differential equations)

- Knowledge of a programming language (MATLAB, C, C++, or Python)

Technological Proficiency and Hardware/Software Required

This course requires access to a personal computer with internet access, and either MATLAB or a text editor and compiler (C, C++, or Python). At USC, MATLAB licenses are available to you from ITS (https://software.usc.edu/matlab/). You will also need access to a scanner or camera to produce digital files for uploading assignments and exams.

Visit https://viterbigrad.usc.edu/technical-support/ for information about technical requirements and electronic tools.

Grading

- Projects: 60%
- Midterm Exam: 20%
- Final Exam: 20%

Notes, Textbooks, and Course Resources

Lecture Notes

A set of notes will be distributed. Together with the lectures and in-class exercises, these constitute all the material needed for the course. This course is based on *Numerical Methods for Partial Differential Equations* at MIT (course number 16.920/2.097/6.339 as taught in 2006–2008), and on the notes developed by Jaime Peraire and Antony Patera, MIT professors at the Departments of Aeronautics & Astronautics and Mechanical Engineering, respectively. Their notes and other material are used and shared with permission from the authors, and such a use is consistent with their Creative Commons License. This year, the course follows closely the material offered by Prof. Alejandra Uranga at USC in 2020. Her notes and materials have been adapted for use with permission.

References

You may find it useful to refer to textbooks on numerical methods in order to better familiarize yourselves with the material, see it from a different perspective, and/or find more details on some topics. The following reference books may be helpful:

- J.H. Ferziger and M. Peric, Computational Methods for Fluid Dynamics, Springer-Verlag
  [*available online through USC Libraries*]
- C.A.J. Fletcher, Computational Techniques for Fluid Dynamics, Vol. 1: Fundamentals and General Techniques, 2nd ed., 1991, Springer-Verlag, ISBN: 3-540-53058-4
  [*available online through USC Libraries*]
- J.C. Tannehill, D.A. Anderson, and R.H. Pletcher, Computational Fluid Mechanics and Heat Transfer, Taylor & Francis

Desire2Learn (D2L, DEN@Viterbi: Course Page) https://courses.uscden.net

The D2L online course management platform from DEN@Viterbi will be used to distribute all course material, ***including assignments***, and to send announcements. Make sure you are able to log in and see the course, then familiarize yourself with the platform.

WebEx (links available on the D2L course page)

If you are new to WebEx, see https://viterbigrad.usc.edu/technical-support/webex/. For on-campus students wishing to attend lectures remotely and for DEN students, live lectures will be conducted over

WebEx. To join the lectures, log on to the course page and select the "Virtual Meetings" tab from the top menu. ***Do not hesitate to ask questions***, either through the WebEx chat (preferred) or by speaking up (interrupt me if you need to). Except when talking to the class, it is good practice to mute your microphone to reduce noise.

Piazza Discussion Forum https://piazza.com/usc/fall2022/20223ame535a/home

You are strongly encouraged to use Piazza to ask questions, make comments, and answer questions from your peers. Piazza is great for asking technical questions, since you can enter mathematical formulae, and insert images and attachments. When discussing project assignments, *do not give out the answers to the assignment tasks!* That would be a violation of the Collaboration Policy. If you are unsure whether you are revealing too much, you can use a private post that only the instruction team can see (under "`Post to`" select "`Individual Student(s)/Instructor(s)`" and then type "`Instructors`" in the corresponding field).

Your participation in answering questions posted on Piazza is strongly encouraged. The top three contributors will receive an extra 5% on their final grade.

Slack https://uscviterbiclass.slack.com

Slack is a messaging platform accessible through a web browser, or thorough desktop and mobile apps. It is available to you as an option for instant-messaging and to create a sense of community with your classmates. Make sure to register with your USC account and learn about Slack by reading the guide at https://keepteaching.usc.edu/students/student-toolkit/classroom/slack/.

Once registered, you will have access to the USC Viterbi School of Engineering Classes workspace (https://uscviterbiclass.slack.com) and to the AME 535a course channels:

- `fall22-ame-535a-general`: *(preferred)* general, announcements, questions, comments
- `fall22-ame-535a-28896`: *(auto generated by Viterbi)* for on-campus students
- `fall22-ame-535a-29065`: *(auto generated by Viterbi)* for DEN students

Use Slack to ask questions or make comments to the whole class (instructor included), to connect with your fellow students (you can see a list on the status bar at the top of the channel, under members), and to collaborate in general. You can also reach the instructor or TA individually (or any other USC member, for that matter) by sending them a Direct Message (DM). Customize your Slack notifications settings so you can stay up to date.

The instruction team will check Slack ***at least twice a day on weekdays and less frequently over the weekend***. **You are encouraged to jump in and answer questions from others.** Use the threads functionality as much as possible to keep things organized (hover over the relevant message and select "`Reply to thread`" text bubble icon from the contextual menu).

Homework and Exam Grading on Gradescope https://gradescope.com

Gradescope will be used for assignment and exam grading. You are responsible for uploading your assignments and exams electronically on time. You will see your grade and comments once they are graded. You will receive an email to your USC email address with instructions on how to register.

Office Hours

Office hours will be held by the instructor and the TA (see first page for days and times) both in-person and live online via Zoom. Find the Zoom links on the course page under the Content topic "Office Hours"). If you cannot make any of the office hour times, send the instructor an email or a DM on Slack to set a different time. You are strongly encouraged to **post your questions on Piazza** at any time.

Office hours are best utilized when you come with *clear questions* and at least *an attempt at a solution*. The goal is for the instruction team to help you clarify the concepts and guide you through your thought process. *It is not meant as a way for you to effortlessly obtain the solutions.*

You are welcome to contact the instructor with questions outside of office hours through email or Slack. However, do not expect an immediate reply (2–3 days delay might be more typical), and keep in mind that some questions are hard to answer in text form: better to keep your emails clear and concise. And if your question is not that simple, then the fastest (and often most efficient) way to get help is via Piazza.

Course Policies

These course policies are designed to help students learn the material effectively, and the course assessment system is designed to best test students on what they really know, and can effectively use, in a real-world context. To ensure fairness, the following rules will be strictly enforced.

Collaboration

- You are strongly encouraged to collaborate on all matters that are not graded.
- You may discuss the projects with each other, the instructor, or the TA but absolutely no written transcript or material can be part of such exchanges. This includes online forums, chats, etc. *If it's not in your head, it isn't yours.* The corollary is that *you must develop and write your own code and solutions.*
- You may not in any case use solutions to problems from past years: these cannot be consulted in any way and would constitute a violation of the above no-written-transcript rule.
- If you use material other than the course notes for the projects, you must cite your references.
- Academic integrity violations will be reported as appropriate.

Project Assignments

- Projects require a significant amount of work and code debugging, so *plan ahead!*
- Projects are due *before* class begins on the due date. To be fair to everyone, late submissions will incur a 20% penalty after the due *time* (2:00pm) and for each successive 24h delay.
- Assignments must be submitted electronically in two parts:
    1) a **PDF file for the report** uploaded to **Gradescope**,
    2) a **zip or tar file with your source code** uploaded to the project submission box in **D2L**.
- In order to receive full credit, solutions must be presented in a clear manner, and show evidence of work: magical one-line answers do not make the cut. *This also applies to the midterm and the final.*

ANSYS Fluent

An optional module on a commercial CFD software – ANSYS Fluent – will be presented. This module will consist of 4 – 5 recorded tutorials on how to use ANSYS for creating a geometry, meshing, and running a subsonic and supersonic test case for an airfoil. A project will be assigned at the end of the module for extra credit up to 10% of your final grade.

ANSYS Fluent is available through MyDesktop, where you can access a virtual desktop that has a number of software available through Viterbi that can be run from your own computers, or by going to one of the Viterbi computing labs at the Salvatori Computer Science Center (SAL). Instructions on how to log on to MyDesktop can be found here. Note that Fluent is available on the Enhanced Desktop on MyDesktop, so make sure you select that option.

Recommendations for Projects

- Ask questions if you have doubts about the material or what you are being asked to do.
- Code for your projects must be written in one of the following programming languages: MATLAB, C, C++, Python.

- The project report you submit should look professional. Organize sections following the project tasks, pay attention to the writing and grammar, and cite your sources. Try placing your figures close to the task which they correspond to and stick to the nomenclature in the assignment handout.
- You are not required to type your report, but if you do decide to handwrite, please *write neatly* so your work is legible.
- You should explain your procedures clearly enough that *the reader must understand what you are doing without looking at your code*. Every step should be documented, and any "educated" reader must be able to reproduce what you have done without guessing. Pseudo-code can often be useful. If your answer/derivation to a question is particularly long, a summary at the end might be a good idea (including for yourself if you are using the derived result later on or coding it).
- If you use a built-in MATLAB function or a programming library, say so and explain what the function does. If you don't know what's under the hood, you shouldn't be using it.
- As a general rule, a correct final answer will not give you full credit; your derivation is at least as important.
- Many questions ask for comments/explanations of the results; these are important. If a question asks you to make a comparison but does not explicitly request an explanation (e.g. compare the convergence rates of the different methods), *you are still expected to provide one. You should think critically about your findings.*
- Submit your code online in a single file (accepted formats: zip, gz, tar, tar.gz) named with your last name, e.g., `Byahut.zip`, and upload it to the D2L course page in the corresponding project section.
- Do not modify your numerical results even if you cannot get the correct result in the end. Your code will be tested for consistency with the submitted results.
- If you know something is wrong with your code/answer, state so even if you don't know what is causing it. Remember: your understanding is being assessed.
- **Do not copy code or any other written material from another student, and do not allow other students to see your work.** Plagiarism is much easier to detect than you might think, and plagiarism-detection tools will be used to check all the submitted programs and reports. *Be mindful of the Collaboration Policy above.*

Topics and Tentative Schedule

Week	Dates	Topics (due times are in Pacific Time)	Reading*
1	23, 25 Aug	I. Introduction	
		Review of linear algebra, floating point arithmetic	
		Overview of PDEs, numerical methods	OV1, OV2
2	30 Aug,	II. Finite Differences: elliptic problems	FD1, FD2
	01 Sep	Consistency, stability, and convergence	
		Formulae: Lagrange interpolation, undetermined coefficients	
		Project 1: FD – *out*	
3	06, 08 Sep	II. Finite Differences: elliptic problems (cont.)	
		Eigenvalue problem, non-rectangular domains	
4	13, 15 Sep	II. Finite Differences: time-dependent linear problems	FD3
		Project 1, Part A: FD Theory – *due 15 Sep, 2:00pm*	
5	20, 23 Sep	II. Finite Differences: convection-diffusion	FD4
6	27, 29 Sep	**Project 1, Part B: FD Implementation – *due 27 Sep, 2:00pm***	
		III. Finite Volumes:	FV1

		Hyperbolic scalar conservation laws, discretization, conservative methods **Project 2: FV – *out***	
7	04, 06 Oct	III. Finite Volumes: Entropy-satisfying schemes, TVD methods **Project 2, Part A: FV theory — *due 06 Oct, 2:00pm***	FV2
8	11 Oct	IV. Solving linear systems: direct methods: Gaussian elimination, LU decomposition	
	13 Oct	***No class: fall recess***	
9	18, 20 Oct	IV. Solving linear systems: iterative methods: Jacobi, Gauss-Seidel, Over/Under-Relaxation, SOR, Multigrid methods **Project 2, Part B: FV implementation — *due 20 Oct, 2:00pm*** **Project 3: SM — *out***	SM1 SM2
10	25 Oct 27 Oct	Midterm Review **Midterm Exam**	
11	01, 03 Nov	V. Finite Elements: Introduction Formulations: strong form, minimization principle, weak form **Project 3: SM — *due 4 Nov, 2:00pm*** **Project 4: FE — *out***	FE1
12	08, 10 Nov	V. Finite Elements: Discretization: bases, projections, mass matrix **Project 4, Part A: FE theory — *due 11 Nov, 2:00pm***	FE2
13	15, 17 Nov	V. Finite Elements: Implementation	FE3
14	22 Nov 24 Nov	V. Finite Elements: Implementation (cont.) **No class: Thanksgiving Break**	FE4
15	29 Nov, 01 Dec	Extra: Special considerations for Navier-Stokes equations *(last day of classes)* Final Review **Project 4, Part B: FE implementation — *due 01 Dec, 2:00pm***	
16	08 Dec	**Final Exam**	

* Reading material is from the notes by Peraire & Patera

Academic Conduct and Support Systems

Academic Conduct

Plagiarism — presenting someone else's ideas as your own, either verbatim or recast in your own words — is a serious academic offense with serious consequences. Please familiarize yourself with the discussion of plagiarism in SCampus in Part B, Section 11, "Behavior Violating University Standards" https://policy.usc.edu/scampus-part-b/. Other forms of academic dishonesty are equally unacceptable. See additional information in SCampus and university policies on research and scholarship misconduct: https://policy.usc.edu/research-and-scholarship-misconduct/.

Support Systems

Student Counseling Services (SCS) (213) 740-9355 – 24/7 on call

https://engemannshc.usc.edu/counseling/

Free and confidential mental health treatment for students, including short-term psychotherapy, group counseling, stress fitness workshops, and crisis intervention.

988 Suicide & Crisis Lifeline 988 or 1-800-273-8255 – 24/7 on call
(Previously *National Suicide Prevention Lifeline*)
https://988lifeline.org/
Free and confidential emotional support to people in suicidal crisis or emotional distress 24 hours a day, 7 days a week.

Relationship and Sexual Violence Prevention and Services (RSVP) (213) 740-9355 – 24/7 on call
https://sites.google.com/usc.edu/rsvpclientservices/home
Free and confidential therapy services, workshops, and training for situations related to gender-based harm.

Office of Equity, Equal Opportunity, and Title IX (EEOTIX) (213) 740-5086
https://eeotix.usc.edu/
Information about how to get help or help a survivor of harassment or discrimination, rights of protected classes, reporting options, and additional resources for students, faculty, staff, visitors, and applicants. The university prohibits discrimination or harassment based on the following protected characteristics: race, color, national origin, ancestry, religion, sex, gender, gender identity, gender expression, sexual orientation, age, physical disability, medical condition, mental disability, marital status, pregnancy, veteran status, genetic information, and any other characteristic which may be specified in applicable laws and governmental regulations.

Bias Assessment Response and Support (213) 740-2421
https://studentaffairs.usc.edu/bias-assessment-response-support/
Avenue to report incidents of bias, hate crimes, and microaggressions for appropriate investigation and response.

The Office of Student Accessibility Services (213) 740-0776
https://osas.usc.edu/
Support and accommodations for students with disabilities. Services include assistance in providing readers/notetakers/interpreters, special accommodations for test taking needs, assistance with architectural barriers, assistive technology, and support for individual needs.

Campus Support & Intervention (213) 740-0411
https://campussupport.usc.edu/
Assists students and families in resolving complex personal, financial, and academic issues adversely affecting their success as a student.

Diversity, Equity, and Inclusion at USC
https://diversity.usc.edu
Information on events, programs and training, the Provosts Diversity and Inclusion Council, Diversity Liaisons for each academic school, chronology, participation, and various resources for students.

USC Emergency UPC: (213) 740-4321, HSC: (323) 442-1000 – 24/7 on call
http://dps.usc.edu, https://emergency.usc.edu
Emergency assistance and avenue to report a crime. Latest updates regarding safety, including ways in which instruction will be continued if an officially declared emergency makes travel to campus infeasible.

USC Department of Public Safety (DPS) UPC: (213) 740-6000, HSC: (323) 442-1200 – 24/7 on call
http://dps.usc.edu
Non-emergency assistance or information.