Final Lab: Star-Lab
15-424/15-624/15-824 Logical Foundations of Cyber-Physical Systems

White Paper Due Date: **Friday, October 26th, 11:59PM**, worth 20 points
Proposal Due Date: **Friday, November 16th, 11:59PM**, worth 80 points
Final Project Due Date: **Thursday, December 6th, 11:59PM**, worth 100 points
Term Paper Due Date: **Friday, December 7th, 11:59PM**, worth 100 points
Presentation Due Date: **Tuesday, December 11th** before the CPS V&V Grand Prix, worth 0 points.
Important submission note: For all project-related submissions, include your name(s) and email(s) for your group at the top. The grading process is different from the other assignments.

The 15-424/15-624/15-824 final project (Star-lab) is an opportunity for you to creatively use what you have learned throughout the *Logical Foundations of Cyber-Physical Systems* course by diving deeply into a CPS problem of your choosing. It is your big chance to achieve fame, glory, and prizes at the CPS Verification and Validation final project competition: **CPS V&V Grand Prix**

What you attempt for your project is completely up to you and your (potential) teammate. There are only two requirements: (1) We want your project to be challenging (you should learn something relevant to the themes of this class) and (2) We want your project to be fun (you should be excited to work on it)!

1 Choosing a Project

There are several general recommended approaches to picking a project:

- Modeling Projects: Pick an interesting system to design, model and verify in KeYmaera X. Most students take this approach.
- Theory Projects: Investigate some new logical/theoretical aspect of CPS.
- Implementation Projects: Hardware and/or software implementation of either an interesting CPS or develop modeling, theorem-proving, etc., technology.

Additionally, students are encouraged to choose course projects that relate to or build off their other work when appropriate. For example, graduate students often have better final projects when their projects are related to their research interests instead of trying to work on several unrelated topics at the same time.

1.1 Advice for all project types

The final projects are very open-ended: your choice of problem is (within reason) completely up to you. However, with great freedom comes great responsibility. A key aspect of the project white paper and especially the proposal is to identify good stepping stones/backup

plans for if and when you run into unexpected problems. Breaking the project up in this way makes it easier to tackle a complex problem. If the full problem becomes too difficult, those stepping stones work as deliverables, and you can discuss the challenges that you have faced during the project and explain the technical reasons why that happened in your term paper. Not only does this approach lead to higher quality, higher scoring and less stressful projects, but it is a good opportunity to practice project planning skills that are useful both in classes and in real life. For example:

- In a modeling project you should think about (and explain to us) how you can simplify your model to make proofs easier, or what simplified properties you can prove if the property you wanted is too hard.
- For a theory project, what are easier theory questions you can answer to help understand the problem before tackling the main problem, and what is relevant research literature you can read/report on the problem?
- For an implementation project, are there any new technologies/libraries you will have to familiarize yourself with for the project? Make sure to budget time for that. What are the most important things to implement, and can you do that in a reasonable amount of time if you run into trouble?

Coming up with a project is up to you. For inspiration, see the projects page on the wiki[1] and the lists of previous projects from previous iterations of the course. Don't let these limit your imagination though! Much of the fun is getting to come up with your own ideas!

2 Project Logistics

As with some of the other labs, the project can either be done alone or in a group of two. The timeline for this project is divided into **five submissions**, whose due dates are listed at the start of this file and on the course schedule page. Guidelines for each of these submissions is given below.

2.1 White Paper

The white paper will set up some preliminary ideas regarding the topic, scope and challenges of your project. You should think of the white paper as pitching your project idea to a funding agency or possible investor in a written analogue of an elevator pitch for the purpose of giving them a chance to see whether there is any interest in what you are suggesting. It is crucial that you communicate concisely and clearly what exactly you are planning to do, why that is a good idea, where you expect challenges and how you plan to master them. Convince the reader why your project idea is worthy and promising.

For example, here are some topics that should be discussed in the white paper for a modeling project:

[1] `https://github.com/LS-Lab/KeYmaeraX-release/wiki/Project-Ideas`

- A generic description of the hybrid system you propose to study for the final project, and how you intend to model the hybrid system. *Cite any references you intend to use as source material.*
- Propose a hierarchy of progressively more complex models and properties of your system, which could be used as stepping-stones to more complex models or controllers. These can include more realistic modeling of the CPS as well as increasingly better controllers.
- You should discuss the core properties that guarantee the correct functioning of the system (for example, safety and liveness) and how you intend to prove or analyze the fulfillment of these properties.
- For properties you intend to prove using KeYmaera X, discuss how you intend to approach the proof (for example, you might propose loop or differential invariants or explain how you might manage branching).
- Identify expected challenges to solicit feedback.
- Identify expected deliverables, i.e., what the output of your project is going to be. These can be, for example, .kyx and .kya files.

Adjust the above list as appropriate for theory or implementation projects. e.g., instead of saying what system you want to model, says which features you want to implement and instead of saying what models you could use as stepping stones, discuss how you could break the features up into smaller, more manageable pieces. Discuss how you would approach theory or implementation problems and what background material/software dependencies/resources you would need and which of that you already have or would need to acquire.

The white paper should be **formatted as a pdf** and be roughly 1 to 2 pages long. The intent of the white paper submission is for you to get feedback on your ideas and how feasible they are, so that you can adapt it for the project proposal. Keep in mind that our feedback on your white paper cannot be effective if your white paper does not effectively communicate what you are trying to achieve or if you have not elaborated your idea sufficiently.

2.2 Project Proposal

The project proposal is a fleshed-out version of the white paper. It will give you a chance to report on what you have achieved with your research/implementation/proofs since the white paper submission. It should also detail what exactly you are planning, what technical challenges your research identified, and what solutions you are planning to overcome them. We expect you to have already achieved a number of first results for the project proposal deadline that give you a clear idea of where the challenges are and what you plan for your final project.

The proposal will help you organize your thoughts about your project and will give the course staff a chance to check that your plans are of the right scope and provide suggestions and advice. As applicable, the proposal should contain the following:

- A descriptive title for your project. You should find a strong descriptive title that best communicates the ideas behind your project.
- A description of the system and why you think it is interesting and relevant to consider.
- A formal model of the system you are considering and a precise explanation and justification of its model.
- A discussion of the desired properties for the system (formalized in dL, if appropriate), and why they are relevant and important, e.g., safety, efficiency.
- Informal explanations why each of the assumptions you make is necessary or useful for the properties you are trying to prove and informal arguments why you do not expect other assumptions to be needed (mind the Cartesian Demon).
- A detailed exposition of related work to show how the problem you are proposing relates to the state of the art in the science of Cyber-Physical Systems.
- A detailed description of each stepping stone for the problem, including how you plan to tackle them, and why they are easier than the more complex problem.
- Each goal and "deliverable" in your project *should be clear*.
- If appropriate, .kyx files for each stepping stone, which includes the controller, the CPS modeled as a hybrid system, and the relevant property.
- By the proposal stage of your project you will likely already have successfully proved a number of simpler properties about your model. Reports on the progress of the proofs and identification of the technical challenges you are facing and how you are planning to solve them or have solved them already.
- Figures can be helpful for illustration purposes. Even if you focus on one particular motivating application, you should broadly discuss where else your findings have applications.

As before, adjust the above appropriately if you have a theory or implementation project. The primary purpose of the project proposal is to justify why the problem that you are solving is interesting and concisely describe the challenges and solicit feedback.

Remember that stepping stones are essential to good project planning. They increase the probability you will have something to deliver, and that is always a good thing. Also remember that the most amazing proofs about the most fancy properties of the most awe-inspiring differential equations and controllers are **not** interesting unless you also clearly motivate, explain, and justify what your model and property says and why they are exactly the right one.

2.3 Final Project, Term Paper, and Presentation

2.3.1 Final Project

The final project submission should be a zip file containing all of your deliverables. These can include code, which should be easily compilable (e.g., use a Makefile and add a README if we need to install anything), and all the .kyx models and .kya proof files that are relevant. You should insert appropriate comments in your hybrid programs or source code. As usual, we are not interested in the sheer number of comments so much as whether you comment the parts that would otherwise be confusing or unclear.

2.3.2 Term Paper

The term paper should discuss the achieved results in sufficient depth for us to assess your work, and compare them to what was originally proposed. There should also be a discussion of the challenges faced and how they were, or not, overcome, as well as any ideas on how to tackle them for the future. It should be about 12-16 pages long.

The term paper should be *structured like a scientific paper*. This requires a bit of a paradigm shift from typical project reports. Imagine that you are presenting your findings to a panel of *very busy experts* in the area. You will need to *engage them quickly*, and convince them of the value of your work. To do so, you should very clearly *outline your contributions* to the field of CPS verification and validation. Make it sound exciting by *highlighting all the potential applications* and by illustrating how you are *pushing the state of the art*. Even if they did not result in all proofs being completed, your insights are valuable! Share them, and explain their relevance.

Remember that CPS experts are not necessarily familiar with your application question, with dL or even the logic-proof approach in general. You should take care to *ensure that they can follow your explanation* of the verification results (e.g., the safety proof). This includes giving the best intuitions that you can regarding what invariants/differential invariants are, how you came up with yours, what they mean intuitively, why they are relevant, and how they helped the proof. Pictorial illustrations of the meaning of the various state variables and invariant constructions in your model can also help communicate your thoughts clearly.

Make sure to *deflect any potential criticism* by defusing worries the reader might have (e.g., by explaining why each simplification in your model is actually okay) throughout the entire document. If they don't believe you got the right model and property, they might not be interested in your proofs.

You are highly encouraged to read up a published paper on CPS verification to get a feel for how they are written. Picking something related to your specific topic would be a big plus, but is not absolutely necessary.

The final paper should contain:

- A brief abstract summarizing the goals and findings of your project.
- An introduction explaining your project and justifying why it is both interesting and

a challenge. Include a discussion of how your project relates to the state of the art as a separate related work section.

- A detailed explanation of the approach you took for your project. This includes in-depth descriptions and justifications of the CPS models and properties that you have studied.

- You have to carefully justify and explain all your models and properties. You need to justify why your models are the right models and why you have reached the right balance between model accuracy and analyzability. For example, studying a system that is so complex you cannot prove it versus studying a system that is so simple it is not realistic enough for actual use. *Unjustified models and properties or models whose differential equations and control principles have not been explained will be ignored in the evaluation of your project.* For all simplifying assumptions in your model, justify to what extent and under which circumstance they are reasonable and explain where they help you. This is also applicable for your differential equation domains, control conditions, etc.

- Describe and explain how you proved the properties. You should provide a brief proof sketch in which you describe how you structured the proof, what invariants and differential invariants you used, what the intuition behind them is and which other important ideas went into your proof, such as steps for taming the arithmetic.

- You are encouraged to illustrate the problem as well as the intuition for important aspects of your solution by graphical illustrations. It is helpful to include relevant illustrations that you are planning to create for the purposes of your project presentation anyhow.

- Conclude with a discussion of what you have learned about the problem you set out to tackle in your project. Describe how what you achieved relates to the goals you set in the proposal. If some goals were not met, explain why. If you achieved goals that you had not planned on, identify them and point out what experience during the project made you consider these goals.

- Summarize the project deliverables.

- It is okay to reuse (and revise) material from your proposal for the term paper if it is still accurate. The better your project proposal was, the more likely will you be able to succeed in delivering a strong final term paper.

- If your project is a team project, please list the work performed by each partner. If you do not feel comfortable making this information publicly available, you may email the course staff this information directly. Alternatively, you can simply state: "equal work was performed by both project members."

- Finally, you should make sure that your term paper provides enough context and information and careful explanation to enable the course staff, reviewers, and judges to fully understand and appreciate the value of your project.

2.3.3 Project Presentation

Your final project presentation will happen on Tuesday, December 11, between 1:00 and 7:00pm, at the CPS V&V Grand Prix. This is arguably the most important part of your project, although it is paradoxically worth 0 points!

You will present your project to a panel of industry experts[2]. It is a *unique opportunity* for you to showcase your CPS verification skills to people who are interested in them for real-world products and applications! Because you will be competing in the CPS V&V Grand Prix, you have **exactly 10 minutes** for your presentation and, in the interest of fairness, you will be cut off when the time is up.

Much of the advice about term papers continues to apply to the project presentation. In addition:

- The talk should be split into the introduction that explain the background and significance of the problem you solve, the middle part detailing the approach you took to solve the problem, and a presentation of the results as well as a summary.
- Thoroughly explain the significance of your project and give sufficient background and potential application areas.
- Highlight what is important about your project.
- Identify contributions, results, and outcomes of your project. Be sure to identify all major conceptual and technical challenges you solved.
- You should place a strong emphasis on an intuitive exposition of your project and make use of visualizations and graphical illustrations supporting your project.
- Slides with too much text are not an effective way of getting the attention of the audience.
- Talks that elide all technical details, however, also make it hard to assess the technical quality and depth of the work.
- When including models and formulas on your slides, make sure they are properly typeset and crucially discuss their intuition. Graphical illustrations continue to be crucial to communicate the parts of models succinctly.
- You should practice your talk often and time yourself to ensure you communicate effectively within the allotted time slot.

[2] `http://lfcps.org/course/lfcps18-competition.html`

- Finally, you should make sure that your term paper provides enough context and information and careful explanation to enable the course staff, reviewers, and judges to fully understand and appreciate the value of your project.
- Have a slide counter on every slide, like 2/6 if you are on slide 2 out of 6.
- Include a *project teaser picture* on your slide and submit this picture at aspect ratio 19:10 to be displayed at 285*150 pixels on the course web page. You are responsible for respecting relevant copyrights.
- Be sure to learn from Kayvon Fatahalian's advice about how to give a clear talk: `https://www.cs.cmu.edu/~kayvonf/misc/cleartalktips.pdf`

When you are preparing the slides for your talk, you may learn what intuition you should add to your term paper. When you give detailed explanations and elaborations in your term paper, you may learn what aspects are important to retain in your project presentation. Communicate clearly, make important points early and often, clearly state what you did, why it is relevant, etc. Practice, if possible in front of other people, so you are sure that you are communicating what you want adequately!

The slides and material for your project presentation is due *before* the CPS V&V Grand Prix.

3 Advice on Proposal and Term Paper

1. If you use LaTeXto write your term paper, BibTeX is your friend for managing citations and references. DBLP[3] is a good source for high-quality bibliographical entries.
2. It is crucial to have a textual description of the model and its dynamics and control principles in the proposal document along with justifications for why you are modeling all its pieces like that. Without a sufficiently comprehensible description, it is hard to validate the model and tell whether you have reached the right accuracy and analyzability tradeoffs. Uncommented program model files are not effective ways of communicating what you are trying to do and why. As in the lecture notes, you should carefully develop and explain and justify the models and properties and explain the rationale behind their design. Make sure to explain and justify the differential equations, not just limit to factually stating that it is the right differential equation for the purpose. For all simplifying assumptions in your model, justify to what extent and under which circumstance they are reasonable and explain why you are making them.
3. A related work discussion is not a discussion limited to where someone has done exactly the same problem before. If that were ever the case, you need to look for a new project, because the problem is solved. Related work is supposed to talk about *related*

[3] `http://dblp.uni-trier.de`

aspects. Discuss things that have some resemblance or similarity with what you are doing. A related work discussion on verification of the International Space Station should not limit itself to a discussion of other papers having done just that. Rather, it should discuss important results where spacecrafts and models and dynamics are discussed. And papers where space and/or aircraft aspects are verified. And papers where superficially different but technically related verification steps are taken. And papers where the problem is even just identified as an important one in the first place. And any other resources you used to come up with your work. Always provide proper citations and references in related work discussions. Related work is also the place to discuss where your work is unique and superior to existing work, as well as the place to be honest about any ways in which prior work is superior.

4. Your proposal does not have to be as detailed and perfect as the term paper. In writing your proposal, keep in mind, though, that the feedback you get can only be as good as the proposal you provide. If you fail to provide sufficient detail or do not explain it properly, feedback will have to be based on guesswork, which is not necessarily effective for you. For preliminary results and proofs, be sure to identify technical challenges and explain them in a comprehensible way to enable the course staff to help you solve them.