Design Tactics

Getting through your project from start to finish

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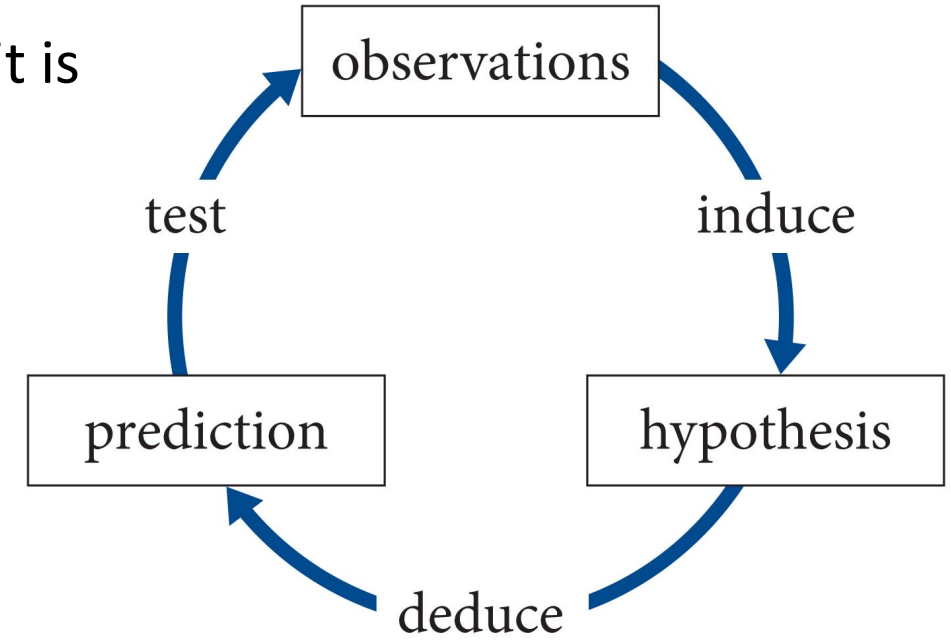
A starting point

- **The Scientific Method** - an iterative process by which we try to construct laws of nature.
- If the prediction is inaccurate, *you modify the hypothesis*
- If the predictions prove to be accurate test after test it is elevated to the status of a law or a theory.

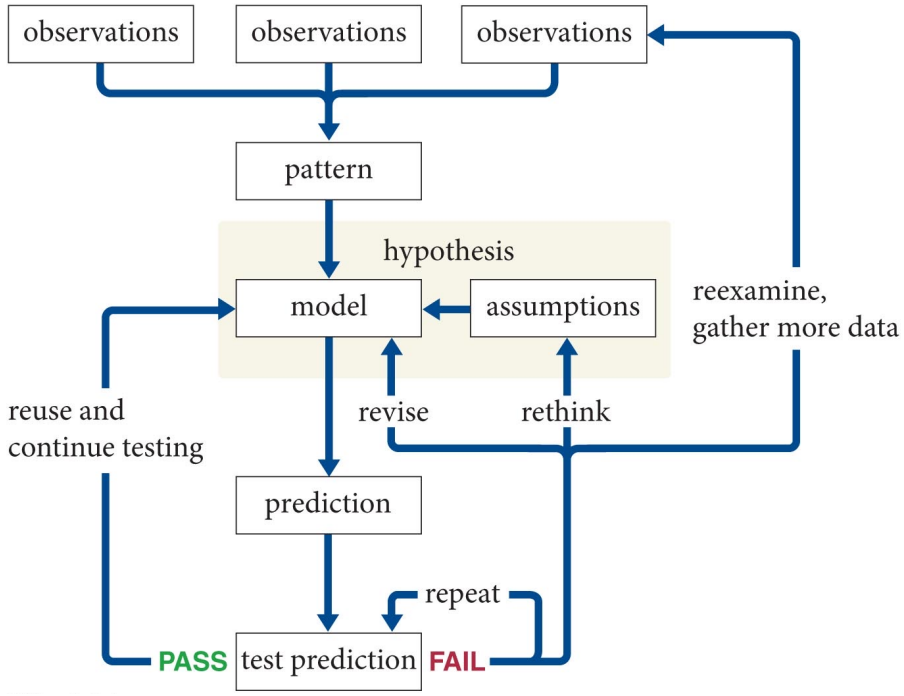


Models ftw

- forming a hypothesis almost always involves developing a **model**
- a **model** is a simplified conceptual representation of some phenomenon.

But you know this …

How do you *actually do stuff?*



Models and Methods

- Abstract the requirements to get to crux of the problem and essential characteristics
- Emphasize selection of appropriate processes and techniques
- Step-by-step from qualitative to quantitative
- Deliberate variation and combination of solution elements of different complexity

OK, you have an idea. Now what?

- Properly defining the problem? The solution?
- How design your experiment or project?
- How do you figure out how to execute the plan?
- How do you work in a team to solve it?
- How to communicate your results?
- Buying $5 models with 50¢ data and other Panglossian problems.

Plan and Play Nice With Others

- The “lone genius” and “flash of inspiration” tropes were never true (ditto for ageism)
- You will have to work in a team
- This stuff is hard work
- It can’t happen incoherently or without planning
  (if it could, someone already did it)
- There are Tools and Tactics that you can use
- There are Processes to guide you

Remember “transferrable skills”?

- Sounds a lot like engineering design? You’re not wrong.
- It is a blurry (and uninteresting) line.
- It is all about doing something systematically, doing it well, and looking at what you are doing objectively.
- We aren’t just *fiddling with the knobs* on the LHC or JWST after all. There are *plans*.

Try to relax

- Speaking of which:
- I didn’t design this to be a high-pressure class
- If it is, let’s figure out why

Activities, broadly

- Conceptualizing – search for solution principles
- Embodying – general arrangement and preliminary ‘shape’ of materials and methods (aka: quick and dirty solution, proof of principle)
- Detailing – finalizing details and making it go (now we are Professionals)
- Throughout – computing, drawing, info gathering, *iteration and feedback*

Skills and activities

- These come up at various phases of the design & implementation of your research
- ***Decision making***
- ***Project management***
- ***Communication***
- ***Collaboration***
- ***Synergies among the skill areas***

Decision making

- Sound and well-reasoned. Not ‘gut feeling’
- Systematically evaluate info & alternatives.
- Ensure clear rationale forms for each
- Establish criteria, eliminate biases.
- Data gathering, brainstorming, and testing
- Fit all this together
  - systematic & iterative approach

Project management

- Focus on actual tasks & activities needed
- Working agreements
- Priorities
- Scheduling
- Record keeping
- Continuous quality improvement

Communication

- More than technical skills needed to succeed
- Must communicate your ideas
- Must communicate with a team
- Must *listen*
- Must *remain calm* and be willing to change your mind
- You must keep the team on the same page

Collaboration

- Again: the solitary genius narrative is a myth
- The great achievements you're thinking of were often based on teamwork and collaboration, or at least building on others' work (or just straight stealing credit)
- This is a way of life for scientists & engineers, the problems are too big to tackle alone
- Also: a skill that needs to be learned

Synergies

- All these skill areas need to be applied together in an integrated way
- Make a working agreement (decision making, collaboration)
- Schedule tasks, assignments (proj. mgmt.)
- Plan when to meet (mgmt., collab., comm.)
- How to document it all (mgmt., comm.)

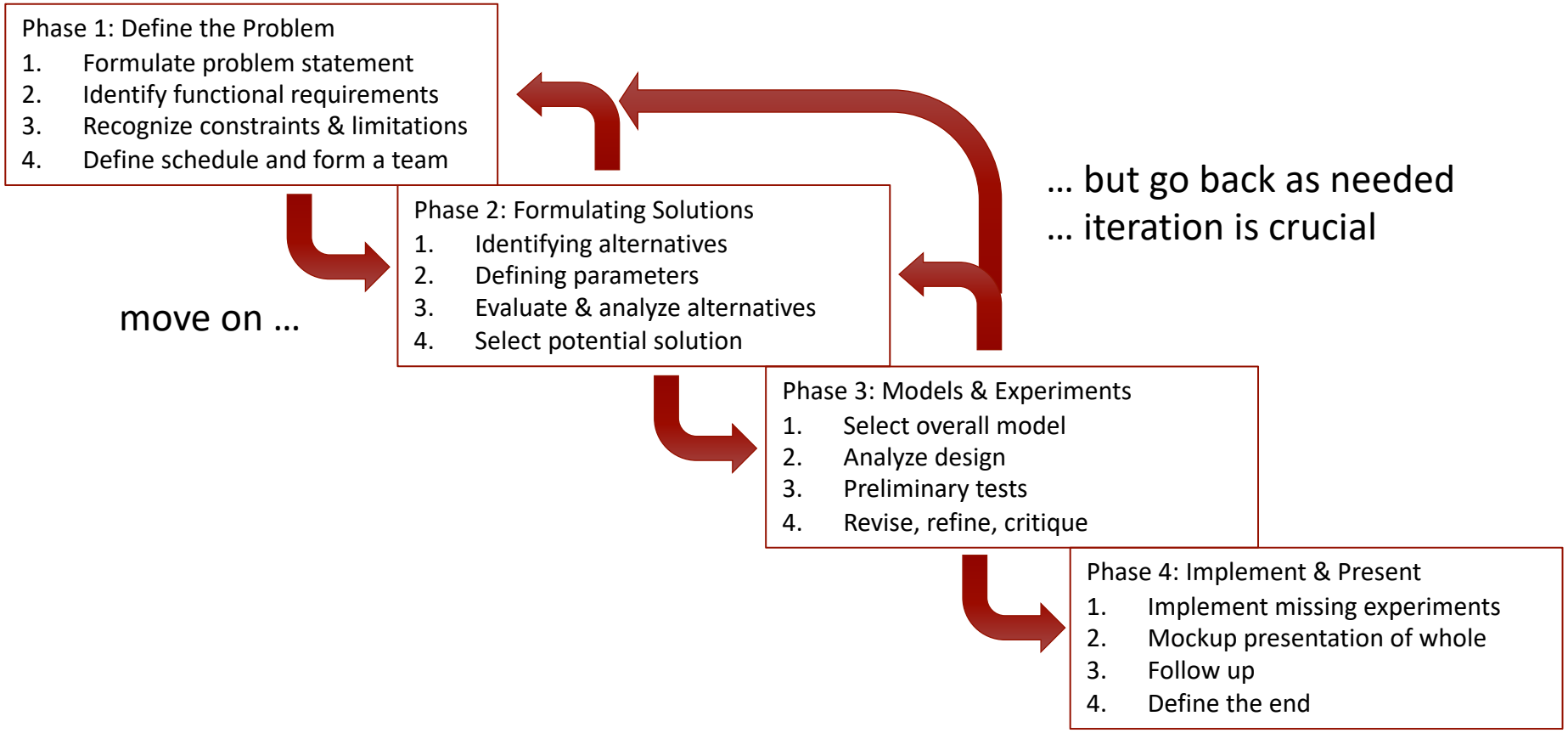
Other characteristics

- Iteration is key – and fast enough!
  - Keep iteration loops small for efficiency
- Stepwise, sequential vs concurrent
  - Stepwise: each step waits on the prior one
    - If it fails or requires revision: start over
  - Concurrent: get the next step *started* ASAP
    - As soon as *possible* or *plausible* perhaps
    - Initial results may be enough to start modeling or designing next experiment, for example
    - What *can* be done in parallel sensibly? What must be simultaneous or sequential?

Phases of design

- Usual steps, but process is iterative
  - Constantly defining & redefining, changing gears
- 1: define the problem
- 2: formulate solutions
- 3: develop models and experiments
- 4: implementation and presentation
- Will come up throughout the course

Phases of design



Yes, this is all a bit much

We could just be screwing around in the lab. We're past the point of my pre-arranging everything to ensure it works out.

But: if we don't start with some discipline and organization to our approach, we'll never add it later.

"We don't rise to the level of our expectations; we fall to the level of our training." – Archilochus

"You do not rise to the level of your goals you fall to the level of your systems" – James Clear, *Atomic Habits*

Phase 1: defining the problem

- Why are you doing this?
  - What has been done already? *literature*
- What is the hypothesis?
  - What are the consequences of it? Testable?
- What do you hope to learn?
- What constraints are present?
  - Physical vs technical vs economic, etc

Phase 1: defining the problem

- 3 basic components of a problem
  - An undesirable initial state
  - A desirable goal state
  - Obstacles that prevent moving from initial to goal state at a particular point in time
- Obstacles:
  - Means to overcome unknown and must be found
  - Mean are known but super complicated – systematic investigation not possible
  - Goals are vague or not formulated clearly – must remove conflicts until they are

Phase 1: defining the problem

Steps for defining the problem	Skills and tools for defining the problem			
	Decision making	**Project management**	**Communication**	**Collaboration**
1. Forming the problem statement	Research & data gathering	Discussing and defining the project	Active listening and probing skills	group formation development
2. Identifying functional requirements	Eliminating biases and overcoming assumptions	Coordinating schedules and planning meetings	Lab record book	
3. Recognizing constraints & limitations	Analyzing key phrases	Establishing working agreements	Composition skills	
4. Defining a schedule & forming a team	Using objective trees Using sketches Clarifying the problem over time	Adhering to your working agreement		

Problems also have *complexity* and *uncertainty*

Phase 1: defining the problem

- Balance of being open-ended enough to not preclude cool ideas but well-defined enough to be actionable.
- Your first attempts will be open-ended and loosely structured. *That's fine*.
- Define *in a way others can understand*
  - You will be part of a team

Phase 1: defining the problem

- Background research: you must know what has been done already
  - Read the literature, keep an open mind
  - Find experts to talk to when you can
  - Place your work in context
  - Avoid duplicating, but with an eye toward *replicating* earlier results as a starting point

Phase 1: defining the problem

- Eliminating biases and overcoming assumptions
  - Relying solely on literature is also not good
    - Mistakes and biases propagate. Think it through.
  - Are you only using the familiar tools?
  - Are you limiting or biasing yourself?
  - Working within a team *can* help
  - It doesn’t mean reinventing the wheel, but keep asking *why,* and *why* again

Phase 1: defining the problem

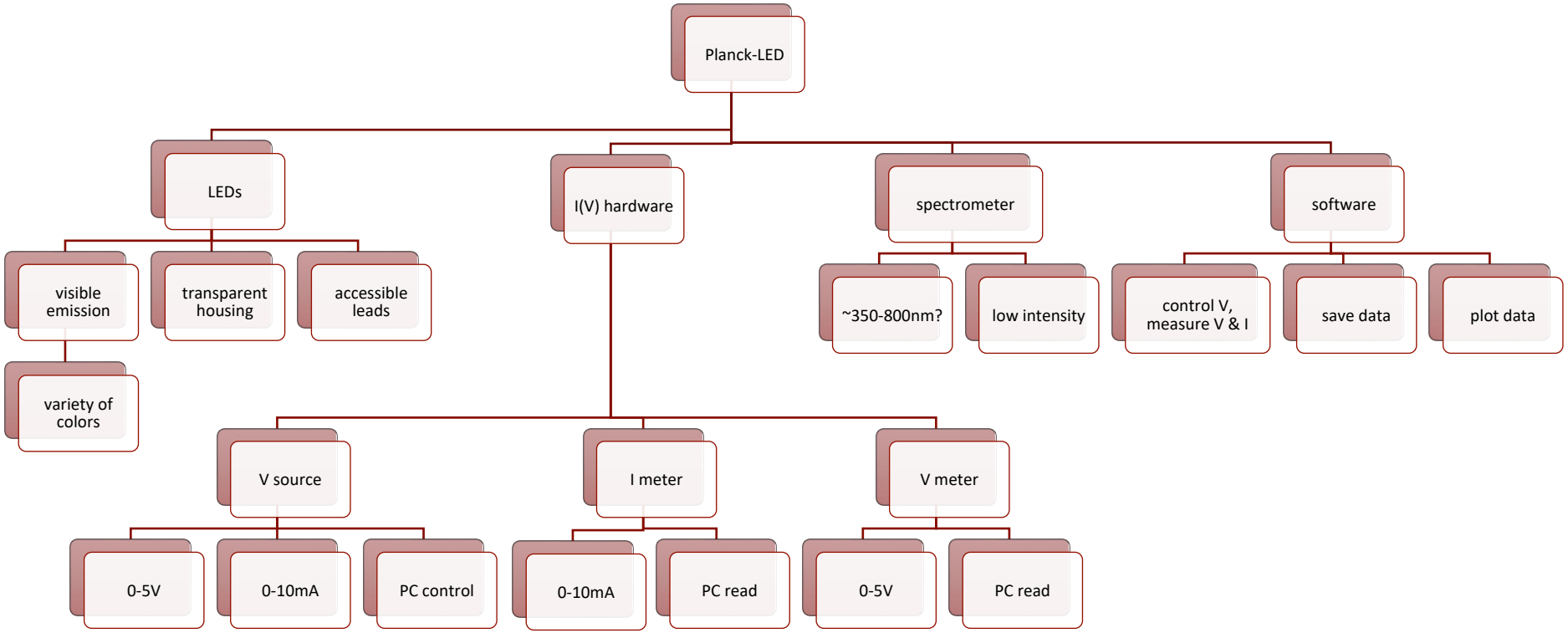
- What is the *actual* problem – requires placing it in broader context
- Example: rare-earth-free permanent magnets
  - On the surface: hard-to-mine materials, etc
  - But also: sticky political problem coupled with horrifically dirty mining processes
  - The *actual* problem is only partly scientific
  - Meaning: moving target!
- Example: parking downtown. Not an engineering problem!

Phase 1: defining the problem

- Identifying functional requirements
  - Must be a need, or an open question
  - Must be one you & your team can *address*
- Recognize constraints & limitations
  - “what” and “how” are shaped by “but” and “however”
  - we can’t *actually* get the LHC to do our experiment, what can we learn from what they’ve already done?

Phase 1: defining the problem

- Objective tree: Planck-LED experiment (PH255)



Phase 1: defining the problem

- Sketches are key. Label and date them.
- Clarify the problem over time; may involve going back to the basic problem statement
- Define a schedule and form a team
  - Regular meeting times/formats/locations
  - Coordinate your schedules, give & take
  - Schedule of ordered activities & reviews
  - Always give a cushion

Phase 1: defining the problem

- Keep track of stuff. E.g., shared files on Box.
- Modify as you go. Change roles as needed.
- Particularly if no one is obviously in charge!

Task	Responsibility	Start date	Target date	Due date	Time est.	Actual time	Percent complete
Literature search	John, Jane	9/13	9/20	9/22	2 hr	3 hr	0 25 50 100
Spectrum analyzer tests	Jane, Rob	10/4	10/11	10/13	1 hr	0.5hr	0 25 50 100
Specimen dimensions	Rob, Joe	10/6	10/11	10/13	1 hr		0 25 50 100
Error analysis	Jane, Beth	10/18	10/25	10/27	3 hrs		0 25 50 100

Phase 1: defining the problem

- Working as a team is by far the hardest part.
- “Look to your left, look to your right. One of those people is going to disappoint you soon.”
- Hahaha. No really. Just be open with each other and learn to compromise. It will be fine.

Phase 1: defining the problem

- You will need to meet.
  - Establish specific times, *start and end* and places
    - Can agree to start each class with a short planning meeting
  - Have a plan for the meeting. Why are you there?
  - Have an end goal – we will finish X
  - If you can't do the last two, don't meet
- Learn to prioritize.
  - 50% finished always beats 0% finished
  - Perfect is the enemy of good

Phase 1: defining the problem

- Leave the meeting knowing when you meet next and why
- Set a working agreement for the meantime
- Set channels of communication

- Be patient with each other, stuff happens.

Phase 2: formulating solutions

- Systematically explore & evaluate alternatives
- Usually more than one solution
- What are the tradeoffs? Options & constraints.
- Solving one aspect may confound another
- Right now, or soon?
  - Who do you need on your team?
  - What techniques are you going to need?

Phase 2: formulating solutions

- Your longer experiments will be like this
- You will be given a *starting* point and must design the path forward
- Some paths are objectively better than others
- But some less-ideal paths are more *reasonable* than others, you will have to compromise

Phase 2: formulating solutions

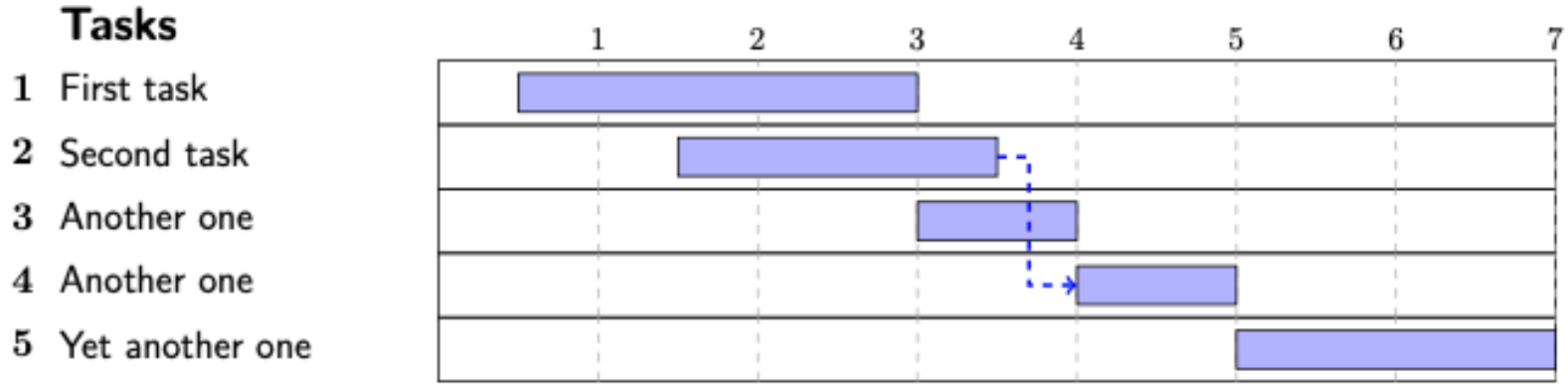
- Decision-making behaviors
  - Recognize dependencies
  - Estimate importance and urgency
  - Persistence and flexibility
  - Failures cannot be avoided
- Define goals, clarify boundary conditions.
- Search for variants, evaluate on merits.
- Decide!

Phase 2: formulating solutions

Steps for formulating solutions	Skills and tools for formulating solutions			
	Decision making	**Project management**	**Communication**	**Collaboration**
1. Defining parameters	Innovation vs. origination	Gantt chart/schedule	Sharing data gathered	Ensuring open participation
2. Identifying alternatives	considering external factors	Keeping records	Writing proposals	Reaching consensus
3. Evaluate & analyze alternatives	Brainstorming		Literature search/biblio.	Manage conflict
4. Selecting solutions	Lateral thinking			Avoid groupthink
	Making estimates			

Phase 2: formulating solutions

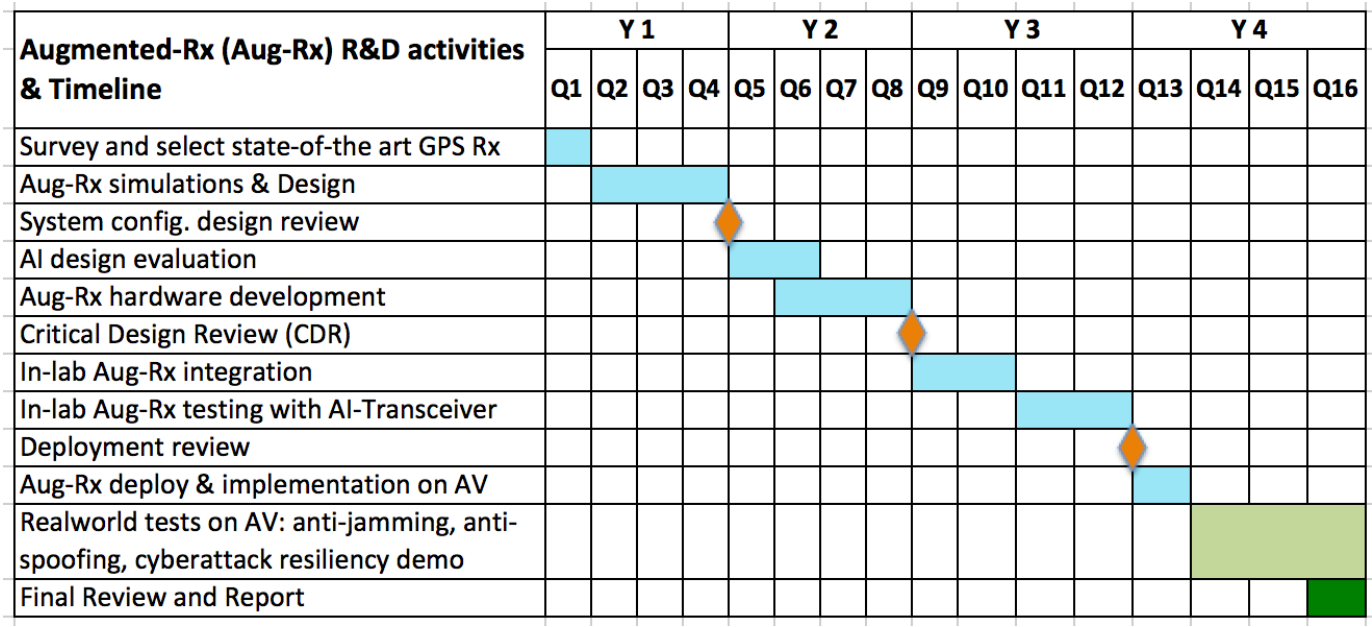
- What is a Gantt chart? A fancy schedule.
- You will see them again. Keys:
  - Identify tasks
  - Identify time sequence
  - Estimated task duration



Phase 2: formulating solutions

- An example from a proposal.
- Easy to make in a spreadsheet

Figure 5: AI-augmented-Rx activities and timeline



Augmented-Rx (Aug-Rx) R&D activities & Timeline	Y 1				Y 2				Y 3				Y 4			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Survey and select state-of-the art GPS Rx																
Aug-Rx simulations & Design																
System config. design review																
AI design evaluation																
Aug-Rx hardware development																
Critical Design Review (CDR)																
In-lab Aug-Rx integration																
In-lab Aug-Rx testing with AI-Transceiver																
Deployment review																
Aug-Rx deploy & implementation on AV																
Realworld tests on AV: anti-jamming, anti-spoofing, cyberattack resiliency demo																
Final Review and Report																

Phase 2: formulating solutions

- Conflict in your group is normal.
  - Keep in mind this is just a class
- It is too early for it yet, hopefully
- So, I'll leave a few things at the end for later

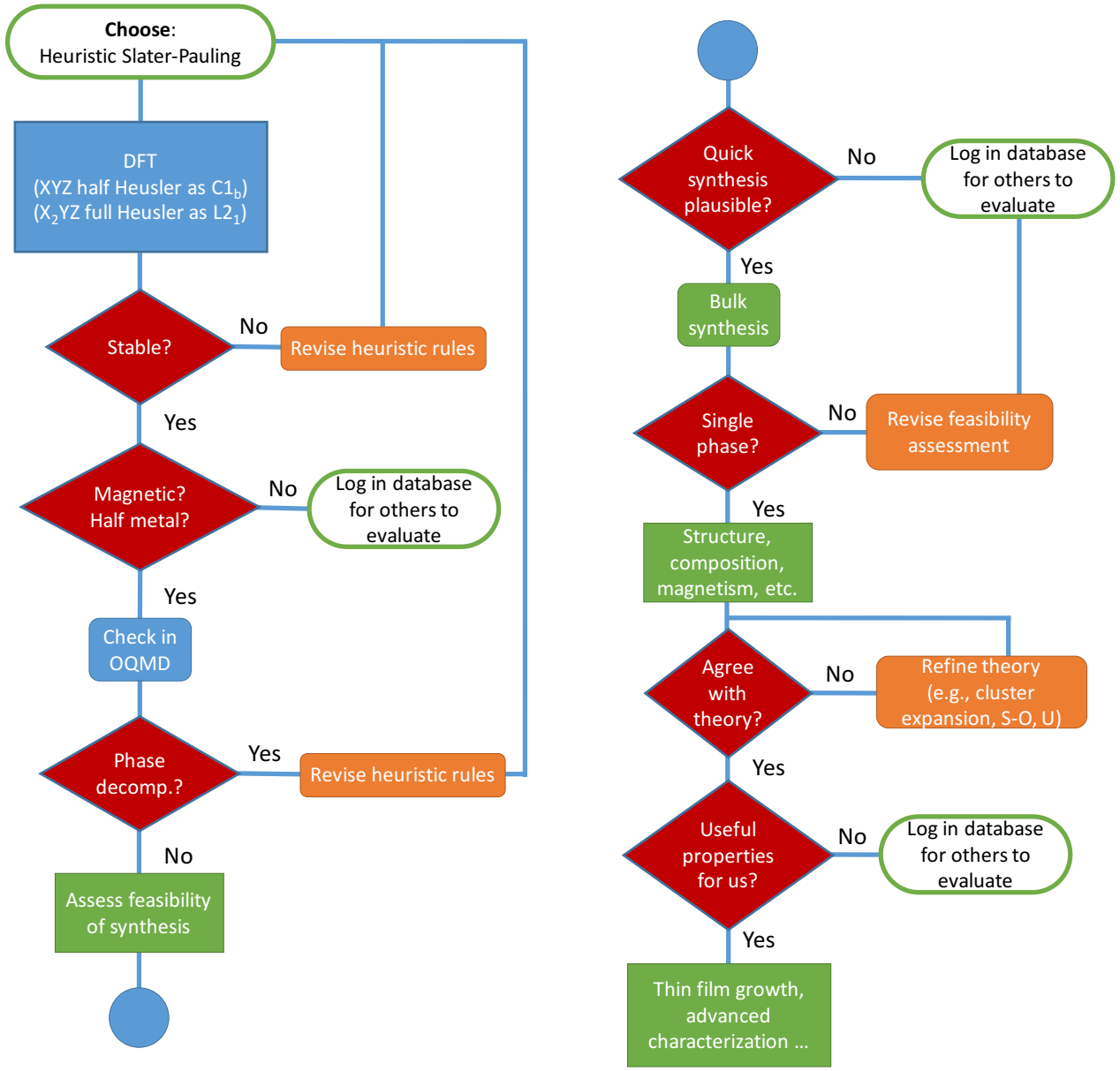
- Note deliverable 1 is a work plan and team survey

Phase 3: models & experiments

- Translate ideas into practice
- Hands-on phase! Prototypes!
- Sub-functions that *were* “black boxes” must now be concrete
- As results and analysis come in …
  - Revise alternatives. Refine or reevaluate problem?
- *The first experiment always goes wrong*
  - but it is only a *failure* if you fail to learn from it

Phase 3: models & experiments

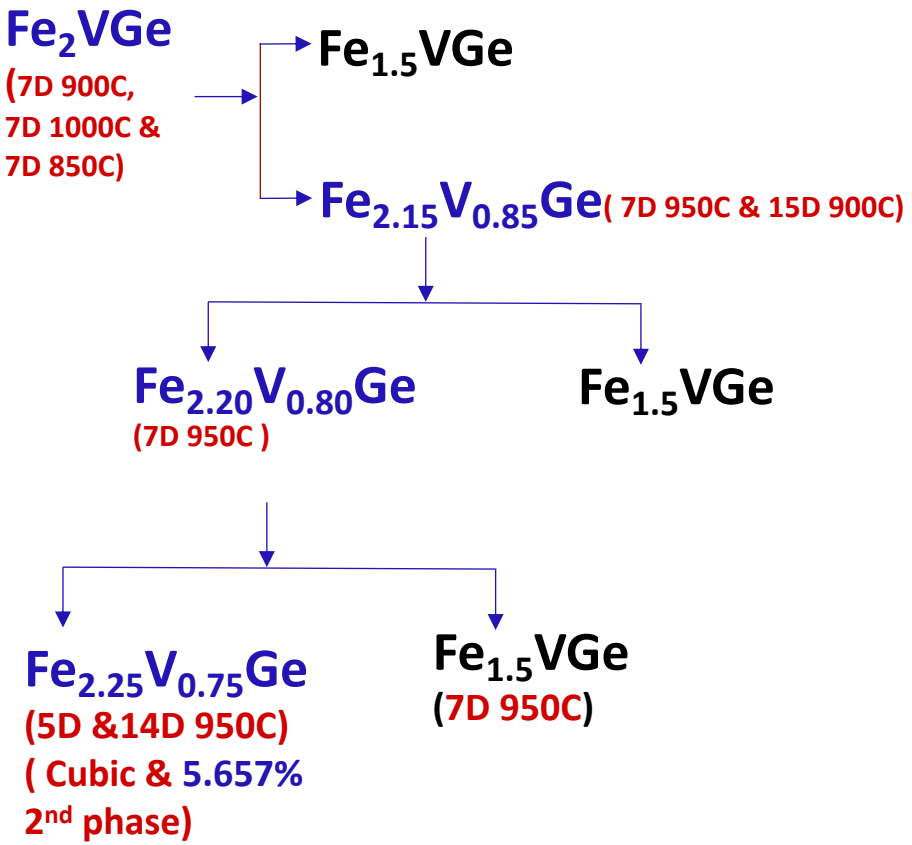
- Example: materials discovery
- Develop algorithm for work
- Plenty of 'start over' steps!



Phase 3: models & experiments

- Example: Fe-V-Ge alloy system
  - At first nothing was stable
  - Revisions based on data charted a path forward
  - Led to a nice bit of work
  - The real key was to forget what we were looking for and focus on what was in front of us

$Fe_{(3-x)}V_xGe$ System



- $Fe_{2.5}V_{0.5}Ge$ (5D,7D &14D at 950C) (Cubic & 0.032% V rich dots)
- $Fe_{2.375}V_{0.625}Ge$ (7D 950) (Cubic & 0.954% V rich dots)
- $Fe_{2.625}V_{0.375}Ge$ (7D 950C) (Cubic & 0.028% V rich dots)
- $Fe_{2.75}V_{0.25}Ge$ (7D 950C) (Hexagonal & 5.110% 2nd phase)
- $Fe_{2.875}V_{0.125}Ge$ (7D 950C) (0.899% 2nd phase)

Phase 3: models & experiments

Steps for developing models	Skills and tools for developing models			
	Decision making	**Project management**	**Communication**	**Collaboration**
1. Selecting a process 2. Performing design analyses 3. Testing the overall scheme 4. Revise, refine and critique	Quantitative and qualitative decisions conducting reviews	Clarifying roles & responsibilities obtaining resources	Writing progress reports Providing feedback Seeking input and feedback	Managing role conflict and Recognizing style differences Eliminating social loafing

Phase 3: models & experiments

- Predictive models: theory leads
- Scale models: try a simpler/smaller version
- Quick & dirty: proof of principle, with understanding it must be redone if successful
- Simulation: e.g., finite element

Phase 3: models & experiments

- Design analysis: driven by preliminary data
- What happened? Did it match expectations?
  - If not, do you know why?
  - If you don’t know why, what to test/check?
  - Is a redesign necessary?
- Was it good *enough*?
  - Where are improvements needed or desired?
- In all stages: prioritize!

Phase 3: models & experiments

- Clarifying roles & responsibilities
  - Do you know who is doing what?
  - Is it better to have 1 or multiple people on a task?
  - Who works well together?
  - Which skills are needed and who has them?
    - If the answer is “no one” who are you gonna call?

Phase 3: models & experiments

- Obtaining resources:
  - I control or negotiate the resources, mostly
  - Make a good case for what you need
  - *Justify* logically, cost effectiveness, utility … ROI
- Progress reports:
  - Keep the above in mind
  - If you want more stuff, indicate you use current stuff well.

Phase 3: models & experiments

- Role conflict: stress of several different obligations at the same time
  - Examine timelines for different concerns & compare
  - Ask for reassignments
  - We all get busy at certain times
  - Redefine your role so it fits schedule better
  - Don’t spend half the time on the last 10%

Phase 3: models & experiments

- Role ambiguity: people aren’t sure of roles
  - Verify everyone understands
  - At end of each meeting, have everyone state what they are expected to do and by when
  - Create sub-teams if needed to ensure skills needed are present
  - Use timelines/Gantt charts and planning tools
  - Use concrete examples to make what contributions should be clear to all

Phase 3: models & experiments

- Style differences: you already get this part
- Dominant? Influential? Conscientious? Steady?
- Try to match tasks and styles when you can
- Learn to adapt when you cannot

- Social loafing: address it right away
  - Be calm and focus on working as a team
  - Can you re-align roles or timelines to help?

Phase 4: implementing & presenting

- Your experiment only has value if people know about it
- Wrong-turns *were* failures if you keep them to yourself
- Organize and lay out your problem & solution
- Find the *best presentation,* possibly at expense of historical narrative

Steps for presenting	Skills and tools for presenting			
	Decision making	**Project management**	**Communication**	**Collaboration**
1. Presenting the final design 2. Implementing and executing 3. Introducing or publishing 4. Following-up	Dealing with last-minute changes Checklisting Seeking a fresh perspective	Ensuring quality Applying continuous quality improvement to your project Reviewing performance	Developing Preparing visual displays Making a presentation Writing final papers/reports	Involving all team members Reviewing team effectiveness Celebrate success!

Phase 4: implementing & presenting

- Visualization and writing: coming soon!
- Involving everyone in the final product
- Writing the report: as above, define roles
- Last-minute shenanigans and Remaining Calm
- Defining success criteria – when are you done?
- Follow-up: sensible to go further?
  - Is this a team that should get together again?

Interlude

- Your experience with this varies *wildly*
- The engineers cover this stuff much better than we do tbh
- But CERN groups and similar large collaborations are clearly very good at this stuff.
- Anyway: this may seem ‘trivial,’ but it is no fun to learn the hard way

The Promised Panglossian Problem

- “It is demonstrable," said he, "that things cannot be otherwise than as they are; for as all things have been created for some end, they must necessarily be created for the best end. Observe, for instance, the nose is formed for spectacles, therefore we wear spectacles. The legs are visibly designed for stockings; accordingly, we wear stockings.” – Voltaire, *Candide*

- *What’s the problem here?*

The Promised Panglossian Problem

- Don’t confuse cause & effect or model & reality.
  - Awfully convenient you found what you wanted …
  - Amazing nature decided to follow your model!
  - Don’t get too excited solving a problem you created
  - Don’t confuse an analogue for the real thing.
- Sometimes there is no moral. Sometimes it's just a bunch of stuff that happened. *That’s fine*, just tell the story. (h/t The Simpsons 7F22)
  - E.g., materials discovery
  - Sometimes there just isn’t an obvious model

Inverse Occam’s razor

- Discuss! What did you get from this?
- Keep this in mind when you write your reports.

Next assignment: mock project outline

- An experiment you've already done
  - Suggest: PH255, but another class/research is OK
- Go through the four stages of of design
- At a high level – think outline
- Charts/sketches a plus but not required
- Example and rubric given

References

- "Tools and Tactics of Design"
  - Dominick et al (ISBN-13: 978-0471386483) – used heavily for this presentation
- "Measurement Systems: application and design"
  - Ernest O. Doebelin (ISBN-13: 978-0072922011)
- "Engineering Design: A Systematic Approach"
  - Pahl & Beitz (ISBN-13: 978-1846283185)
- "Inverse Occam's razor",
  - Igor Mazin. Nat. Phys. 18, 367–368 (2022)
  - https://doi.org/10.1038/s41567-022-01575-2

Extra sides on formulating solutions

When your group is having problems …

Phase 2: formulating solutions (FOR LATER)

Managing conflict

What	How
Acknowledge that conflict is normal and to be expected	Build in time for debate; ask for feedback and debate
Acknowledge personal biases	Use active listening; judge content, not delivery; use others as a sounding board
Understand project definition and constraints	Review tasks to be done; assess resources needed; determine who does what and when
Encourage open participation	Ask others to contribute, listen to all alternatives
Acknowledge that participants are new to the task	Take time to know task; take time to get to know strengths & weaknesses of participants
Seek to understand ideas of others	Before getting those around you to understand your perspective, try to understand theirs. You may realize you are closer to theirs than you thought
Don't always be right	Acknowledge that others have good ideas. Don't immediately correct others; tolerate imperfection

Phase 2: formulating solutions (FOR LATER)

- Steps if your team is avoiding conflict
  - Decide to explore fully pros & cons of each issue that comes up, even if it means a longer meeting or extra stress for a while
  - Before meeting closes, have everyone summarize next steps they are responsible for & the reason for them
  - Start meetings on time
  - Create an agenda of issues for the meeting
  - Appoint someone as discussion lead to keep on track

Phase 2: formulating solutions (FOR LATER)

- Steps if your team is avoiding too accommodating
  - Have team members who argue for or against fully explain their rationale and defend it against counterarguments
  - Start discussions about pros/cons of an issue by having each write down their argument, then read aloud & discuss
  - Appoint a different person for each meeting to act as facilitator, they should ask for everyone's input
  - Evaluate each idea against the criteria for a good decision and not just because it was suggested

Phase 2: formulating solutions (FOR LATER)

- Steps if your team is fighting
  - Refrain from passing judgement or assessing blame if things don’t go right.
  - It doesn’t matter who broke it, just figure out how to fix it.
  - Divide cliques and meet in different subgroups
  - Ask members to defend an idea they disagree with to get them to see positive sides of an alternative they didn’t consider
  - Spend 1 meeting reviewing principles of active listening
  - Remind team that each idea needs to be evaluated against criteria of best solution & not origin of the idea

Phase 2: formulating solutions (FOR LATER)

- Steps if your team is too quick to compromise
  - Refrain from taking a vote to decide an issue, even if it prolongs discussion time
  - Appoint someone as the results checker – after decision is made, they walk the team through the evaluation criteria and compares decision to criteria
  - Encourage debate – have each member state pros & cons of one alternative, have rest respond

Phase 2: formulating solutions (FOR LATER)

- Signs your team is collaborating
  - Members feel free to communicate openly with each other
  - Members listen actively
  - Criteria for a good solution are what drive discussion, not frustration or anger and blame
  - Everyone understands that the best solution is best for the group regardless of where the ideas came from
  - All alternatives are explored, and alternatives are combined to create even better solutions
  - Everyone understands the steps in the process and agrees about what is the best next step

Phase 2: formulating solutions (FOR LATER)

- Avoid groupthink
  - not disagreeing out of fear of being ostracized
- There are outside pressures
- Watch for dominating behavior. Resist the urge to interrupt