Engineering design process

Introduction

Marco Teran

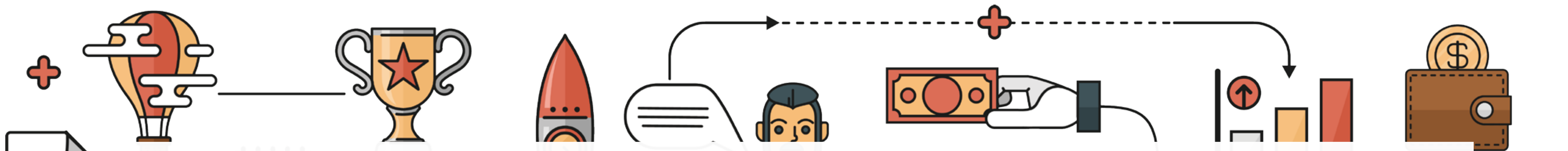
Engineering design process

The engineering design process is a common series of steps that engineers use in creating functional products and processes.

- **The process is highly iterative** - parts of the process often need to be repeated many times before another can be entered - though the part(s) that get iterated and the number of such cycles in any given project may vary.

- It is a **decision making process** (often iterative):
  - Basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective.
  - Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing and evaluation

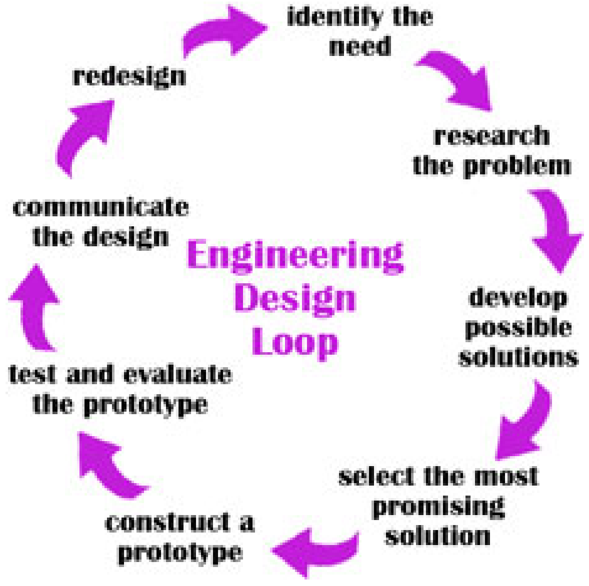
Common stages of the Engineering Design Process

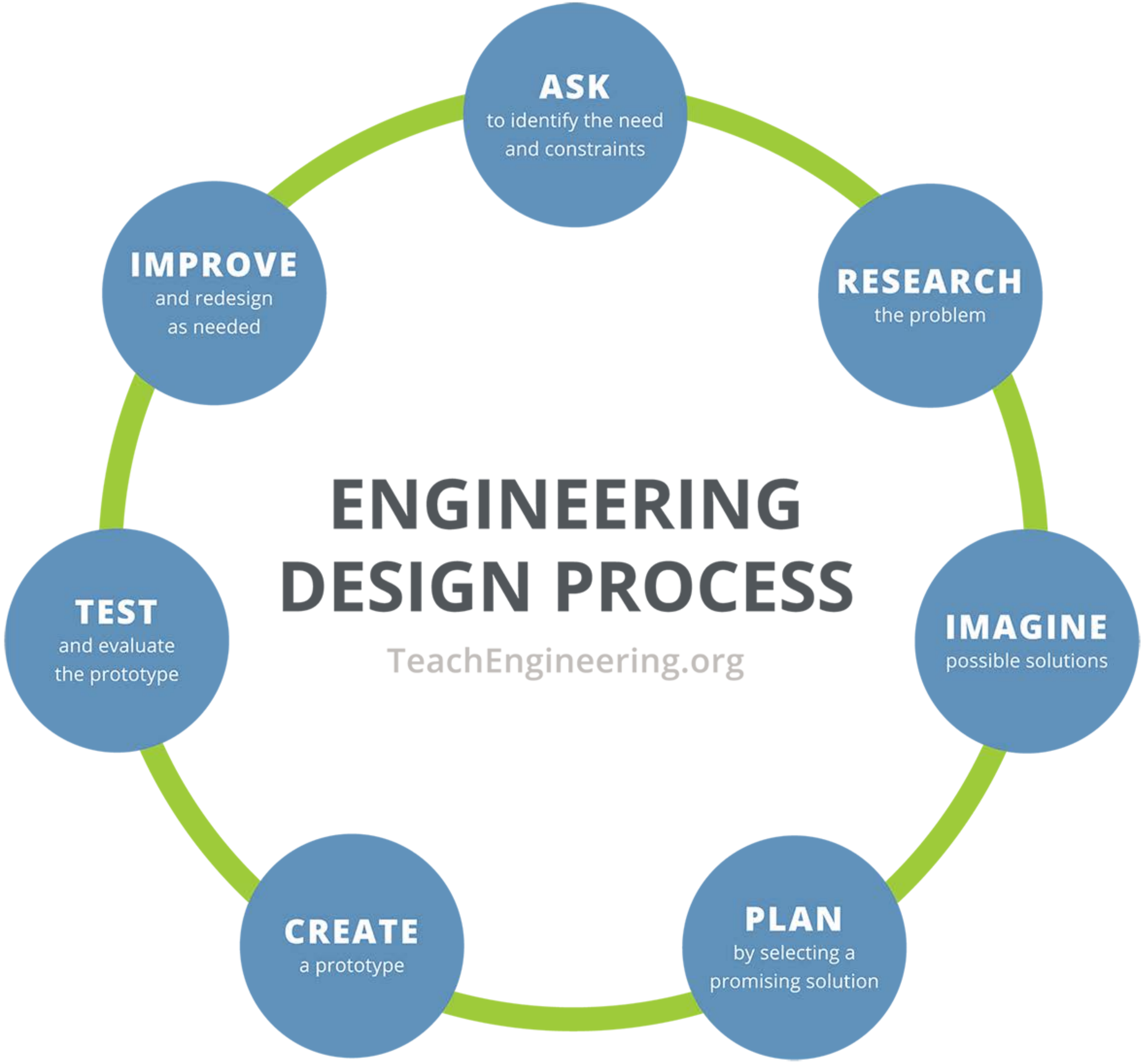


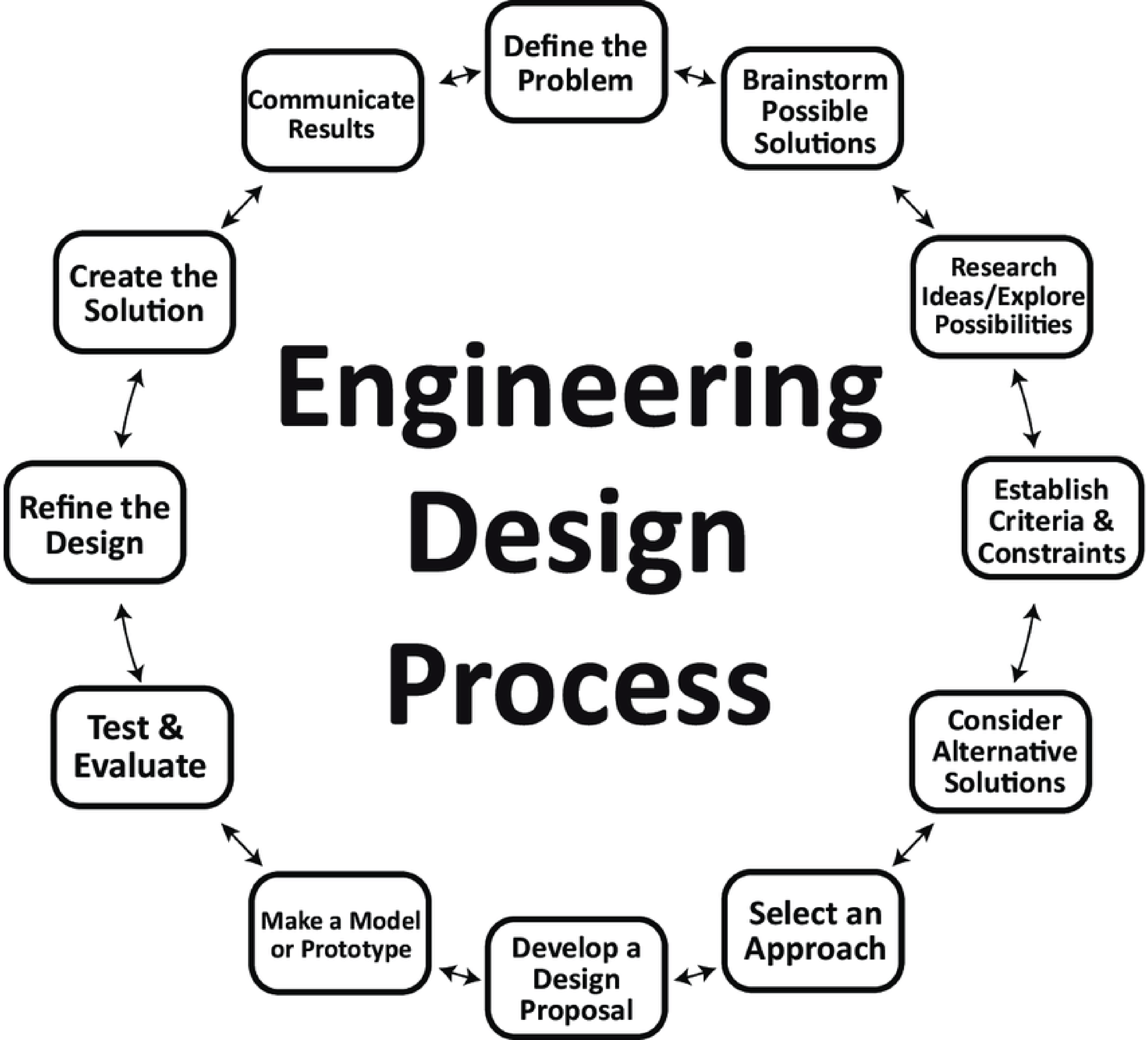
- It's important to understand that there are various framings/articulations of the engineering design process
- *Different terminology employed may have varying degrees of overlap*
  - Affects what steps get stated explicitly or deemed "high level" versus subordinate in any given model
- Iterative — Repetitive
- The Steps of the EDP may be conducted many times, resulting in the generation of many designs and prototypes.

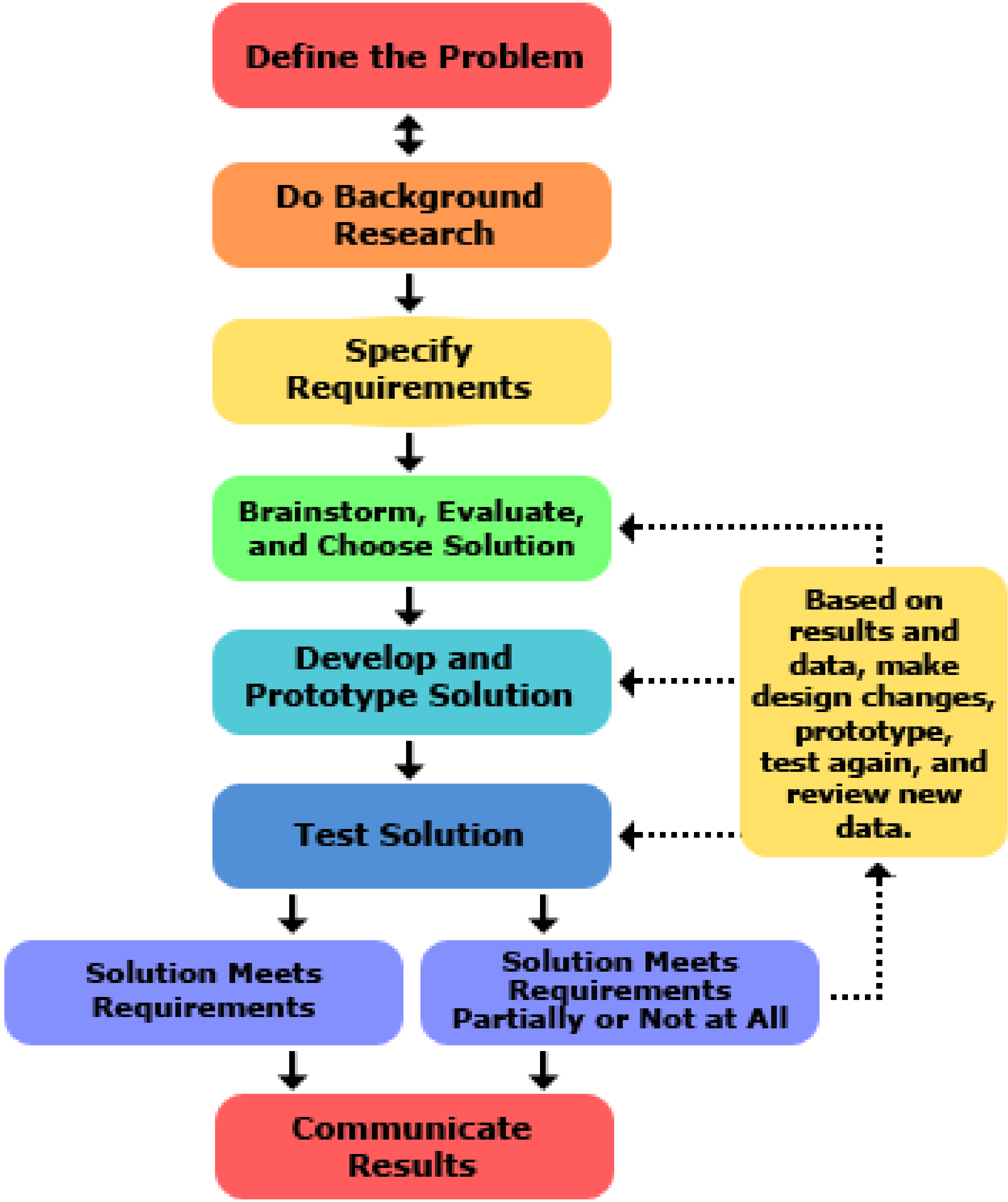
Common stages of the engineering design process

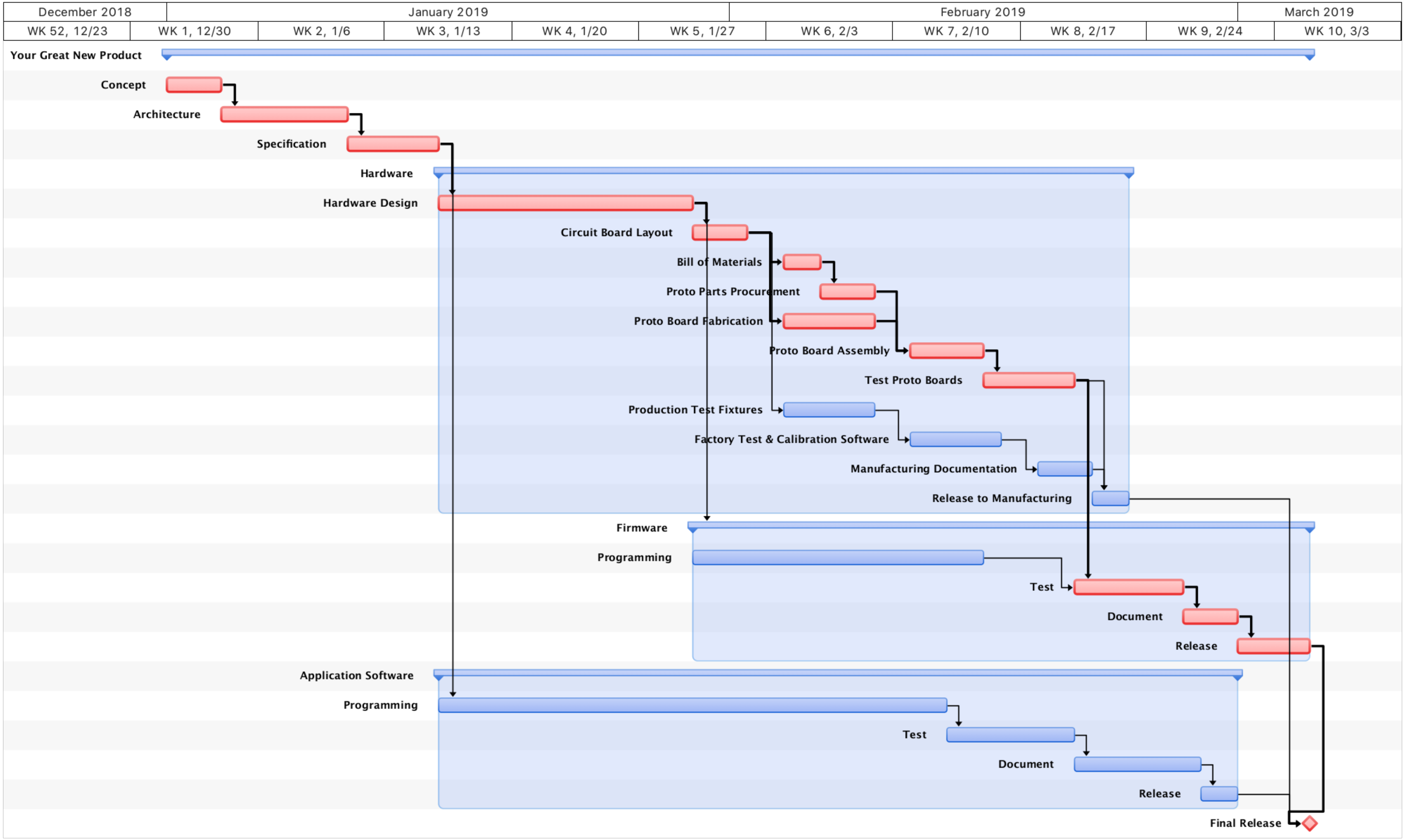
1. Define the problem/Identify the need
2. Research the problem
3. Brainstorm/develop solutions
4. Select the solution
5. Build/construct prototype
6. Test and evaluate prototype
7. Communicate the design
8. Redesign (as needed)




ENGINEERING DESIGN PROCESS
TeachEngineering.org
ASK to identify the need and constraints
RESEARCH the problem
IMAGINE possible solutions
PLAN by selecting a promising solution
CREATE a prototype
TEST and evaluate the prototype
IMPROVE and redesign as needed

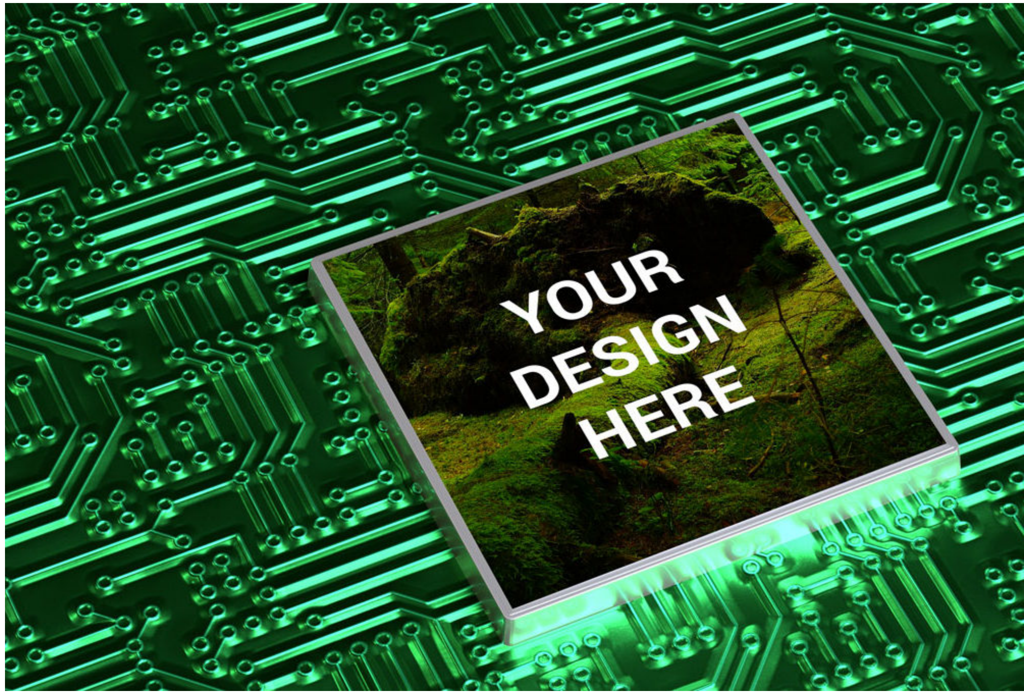

Engineering Design Process
Define the Problem
Brainstorm Possible Solutions
Research Ideas/Explore Possibilities
Establish Criteria & Constraints
Consider Alternative Solutions
Select an Approach
Develop a Design Proposal
Make a Model or Prototype
Test & Evaluate
Refine the Design
Create the Solution
Communicate Results


Define the Problem
Do Background Research
Specify Requirements
Brainstorm, Evaluate, and Choose Solution
Develop and Prototype Solution
Test Solution
Solution Meets Requirements
Solution Meets Requirements Partially or Not at All
Based on results and data, make design changes, prototype, test again, and review new data.
Communicate Results


December 2018
January 2019
February 2019
March 2019
WK 52, 12/23
WK 1, 12/30
WK 2, 1/6
WK 3, 1/13
WK 4, 1/20
WK 5, 1/27
WK 6, 2/3
WK 7, 2/10
WK 8, 2/17
WK 9, 2/24
WK 10, 3/3
Your Great New Product
Concept
Architecture
Specification
Hardware
Hardware Design
Circuit Board Layout
Bill of Materials
Proto Parts Procurement
Proto Board Fabrication
Proto Board Assembly
Test Proto Boards
Production Test Fixtures
Factory Test & Calibration Software
Manufacturing Documentation
Release to Manufacturing
Firmware
Programming
Test
Document
Release
Application Software
Programming
Test
Document
Release
Final Release

Definition Stages

- Many engineering and software teams skip these steps and figure it out as they go
- When the schedule is tight (as it usually is), they are anxious to dive in and start the “real” work of design and coding.
- Changing your mind in the definition stages is cheap
- Changing your mind or having to correct for poor architectural decisions later in a project can be costly.
- You want to minimize the chances of having to scrap expensive tooling and hardware by more carefully thinking it all through up front
- This is not to say that you might not want to do some rough exploratory designs and prototyping up front to test out some ideas



Time spent wisely on the front end can save a lot of time and money in the long run

Research

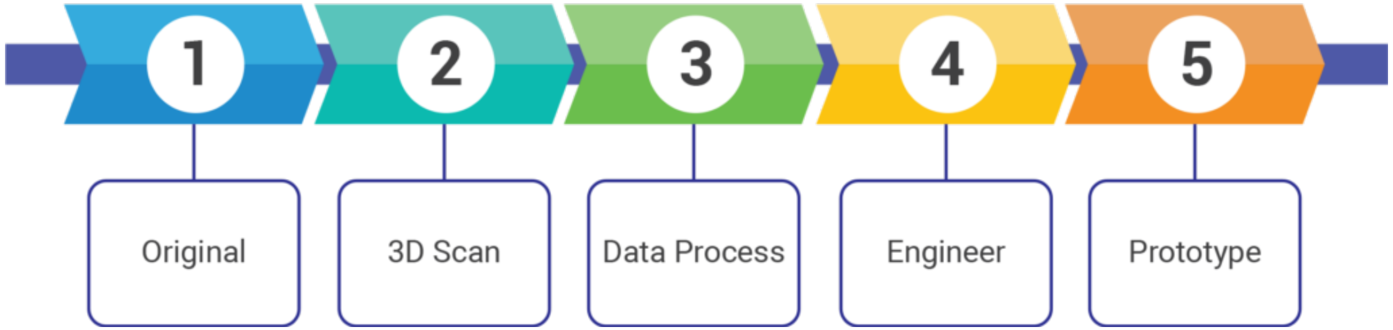
- Various stages of the design process (and even earlier) can involve a significant amount of time spent on locating information and research.
- Consideration should be given to the existing applicable literature, problems and successes associated with existing solutions, costs, and marketplace needs.
- The source of information should be relevant.
  - Reverse engineering can be an effective technique if other solutions are available on the market.
  - Other sources of information include the Internet, forums, available documents, and experts available.

Research

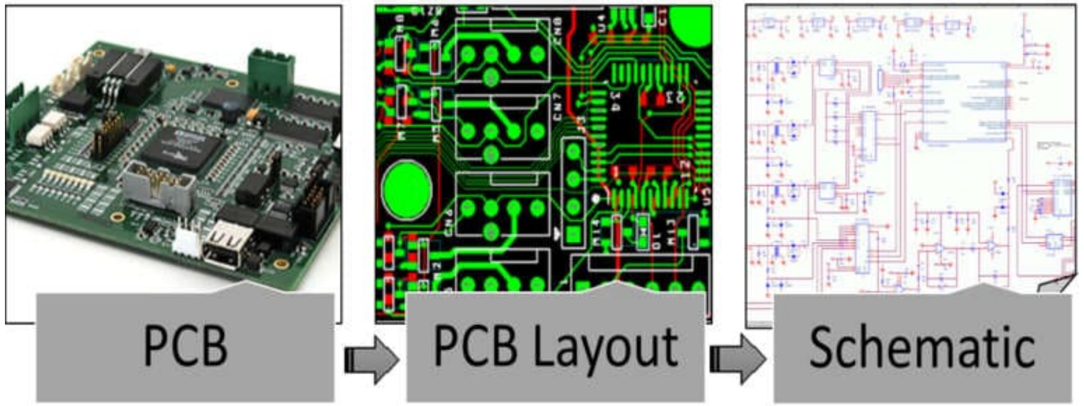
- Various stages of the design process (and even earlier) can involve a significant amount of time spent on *locating information and research*.
- Consideration should be given to the **existing** applicable literature, problems and successes associated with existing solutions, costs, and marketplace needs.
- The source of information should be relevant:
  - **Reverse engineering** can be an effective technique if other solutions are available on the market.
  - Other sources of information include the Internet, forums, available documents, and experts available.
- Collect information about concepts relevant to the problem statement.
- Take notes (in own words) from valid sources.

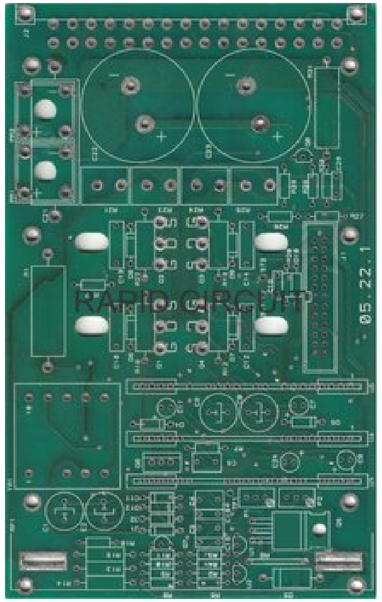
Reverse Engineering

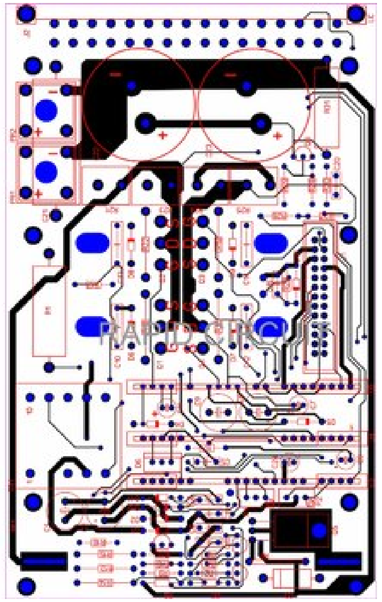
- The process of conducting research on how a solution (object or process) works, in order to understand what works well and what does not work well

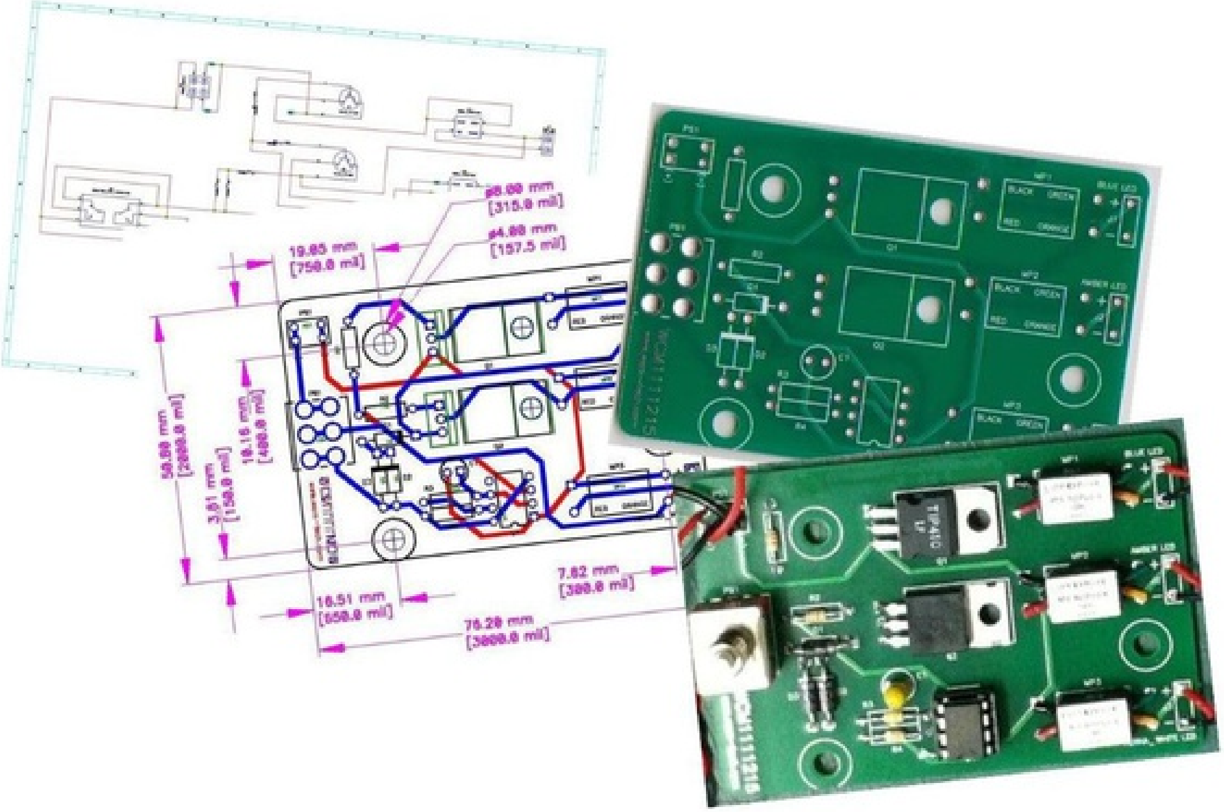


Reverse Engineering









Design requirements

- Establishing design requirements and conducting requirement analysis, sometimes termed **problem definition** is one of the most important elements in the design process
- The design requirements control the design of the product or process being developed
- These include basic things - determined after assessing user needs:
  - The functions
  - Attributes
  - Specifications
- Some design requirements include hardware and software parameters, maintainability, availability, and testability.

- Criteria — A limitation or restriction
- Constraint — Standards against which something must be judged
  - Minimum expectations assigned for a design

Define the Problem/Identify the Need

- Make clear the need for a solution.
- Identify the criteria and any constraints.

The Problem: Client Statement

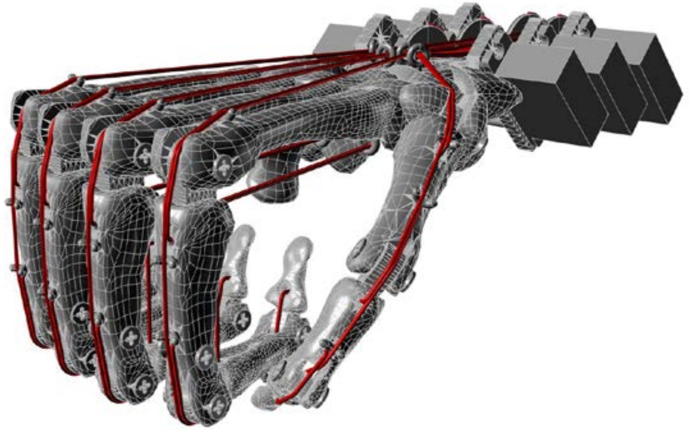
The doctor hires you to design and build an assistive device (hand). Due to cerebral palsy, a fine motor disorder, a 12-year-old boy has difficulty conducting everyday activities.

- Assistive hand device can grip a cup that increases in weight.

Client's Criteria

- Must be able to grip a cup, that increases in weight.
- Cup gripped must contain at least 200 ml of sand.
- Must look somewhat like the human hand.
- Can be manipulated with hands.
- Costs equal to, or less than, $50.00.
- Is completed in 5 days.

Research relevant topics:

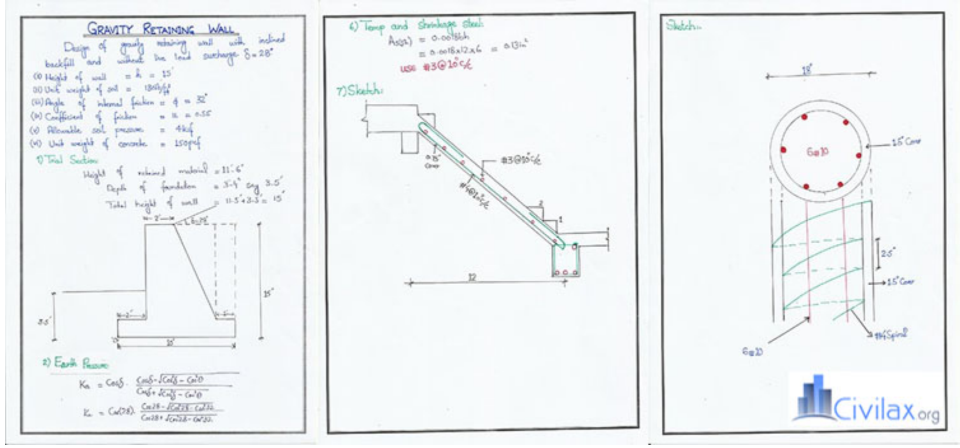


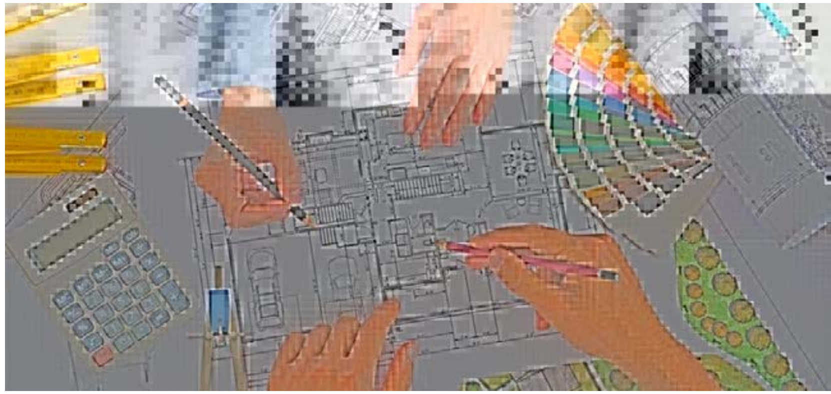
- the structure of the human hand
- the function of the human hand

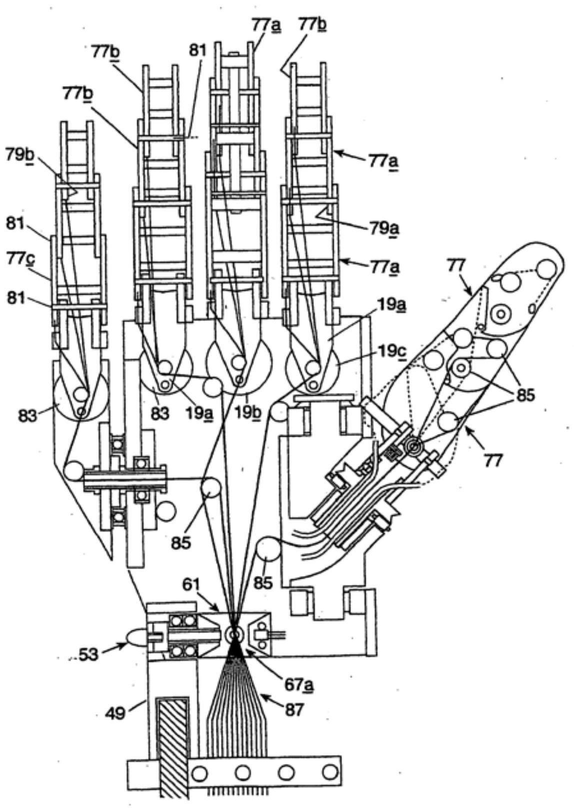
And then:

Conduct reverse engineering:

- assistive hand devices that have already been invented
- assistive technologies for gripping cups
- the pros and cons of both (above) technologies

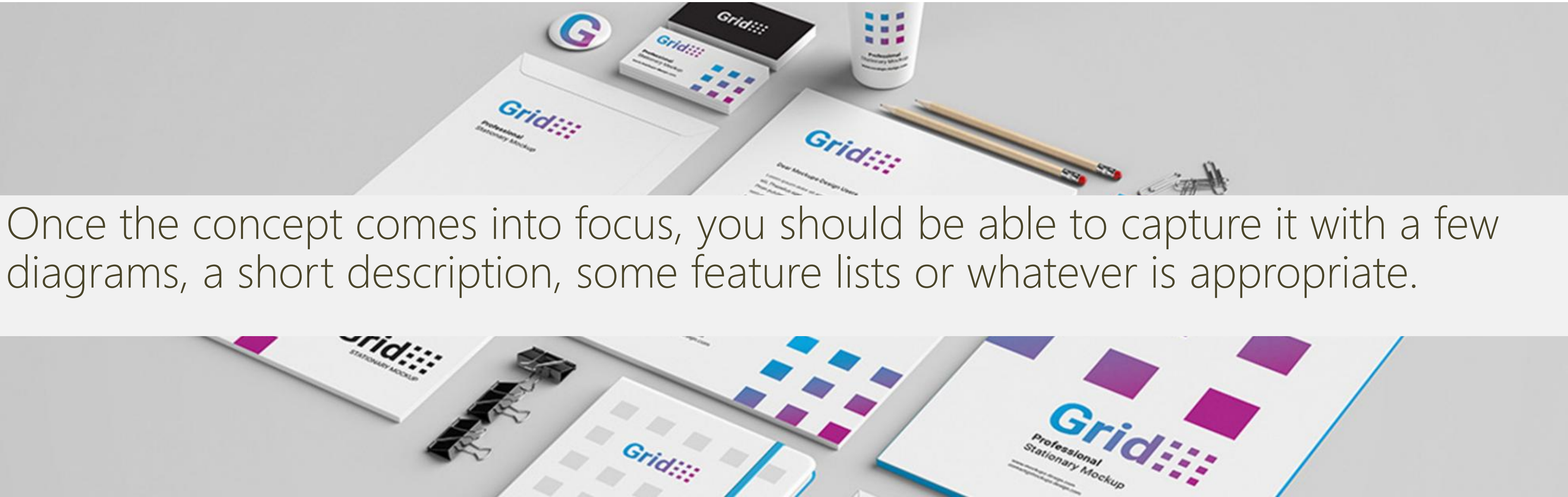






CONCEPT

- What the product is and **not** how to design and make it
- Concentrate on the features and goals
  - Brainstorm
  - Build some quick mockups
- Think about who the target audience is and their needs
- Get input from marketing or the customers themselves



Once the concept comes into focus, you should be able to capture it with a few diagrams, a short description, some feature lists or whatever is appropriate.

Concept Generation

- A concept study (conceptualization, conceptual design) is often a phase of project planning that includes producing ideas and considering the pros and cons of implementing those ideas.
- This stage of a project is done to minimize the likelihood of error, manage costs, assess risks, and evaluate the potential success of the intended project.
- In any event, once an engineering issue or problem is defined, potential solutions must be identified.
- These solutions can be found by using ideation, the mental process by which ideas are generated. In fact, this step is often termed Ideation or "Concept Generation."

Concept Generation

The following are widely used techniques:

- trigger word - a word or phrase associated with the issue at hand is stated, and subsequent words and phrases are evoked.
- morphological analysis - independent design characteristics are listed in a chart, and different engineering solutions are proposed for each solution.
    - Normally, a preliminary sketch and short report accompany the morphological chart.
- synectics - the engineer imagines him or herself as the item and asks, "What would I do if I were the system?"
    - This unconventional method of thinking may find a solution to the problem at hand.
    - The vital aspects of the conceptualization step is synthesis.
    - Synthesis is the process of taking the element of the concept and arranging them in the proper way.
    - Synthesis creative process is present in every design.
- brainstorming - this popular method involves thinking of different ideas, typically as part of a small group, and adopting these ideas in some form as a solution to the problem

Brainstorm Solutions

Generate ideas that will solve the problem (as defined in step 1, Define the Problem/Identify the Need).

1. Generate as many ideas as possible.
2. Withhold judgment and be respectful.
3. Encourage wild ideas.
4. Build on others' ideas as much as possible

Preliminary design

The preliminary design, or high-level design bridges a gap between design conception and detailed design

- Particularly in cases where the level of conceptualization achieved during ideation is not sufficient for full evaluation.

- So in this task, the overall system configuration is defined, and schematics, diagrams, and layouts of the project may provide early project configuration.
- During detailed design and optimization, the parameters of the part being created will change, but the preliminary design focuses on creating the general framework to build the project on
- Objectives
- Requirements: functional and non-functional
  - list

Detailed design

- Detailed Design (Detailed Engineering) phase, which may consist of procurement of materials as well.
- This phase further elaborates each aspect of the project/product by complete description through solid modeling, drawings as well as specifications.
- Computer-aided design (CAD) programs have made detailed design phase more efficient.

Primera entrega: presentación

- Slide 1: Nombre del Proyecto, Integrantes (Nombres y carreras)
- Slide 2: Descripción del problema
- Slide 2: Requerimientos del cliente
- Slide 3: Concepto de la solución. ¿Qué es?
    - Objetivos
- Slide 4: Roles – cliente, usuario final, desarrolladores, administradores, etc.
- Slide 4: Requerimientos funcionales
- Slide 5: Requerimientos no funcionales
- Slide 6: Mockup (diseño simple, cómo se vería)

Preliminary design

ARCHITECTURE

- Starting to piece together a design, but only in very broad strokes.
- All the pieces will fit together at a very high level
- Focus on what key pieces of technology you will need
    - Special software modules
    - Communications (hardware and protocols)
    - Data storage, sensors
    - Investigate the tradeoffs between different options with an eye towards creating a simple and elegant solution.

ARCHITECTURE

A system or product architect should have a broad range of knowledge or experience, the ability to see several steps ahead, and a healthy dose of creativity.

- Quickly see the pros and cons of different approaches
- See outside the box and bring in ideas that are different than the standard way of doing things
- Traditional methods are often the best, but sometimes a simple but key switch in the approach can lead to some big breakthroughs.

ARCHITECTURE

- Starting to piece together a design, but only in very broad strokes.
- All the pieces will fit together at a very high level
- Focus on what key pieces of technology you will need
    - Special software modules
    - Communications (hardware and protocols)
    - Data storage, sensors
    - Investigate the tradeoffs between different options with an eye towards creating a simple and elegant solution.
- Architectural documents explain to everyone how the main pieces fit together

DESIGN SPECIFICATION

- The design specification dives much deeper into the details, typically in a more formal document.
- Some of the design specifications may be useful in a **customer** or **product specification** later, but the **main purpose** at this point is to **guide the developers**.
- The design specification tells the engineers and programmers more about **how to make it work and their requirements and constraints**.

DESIGN SPECIFICATION

Items to include in a specification:

- Power supply requirements
- Measurement precision and accuracy
- Operating and storage temperatures
- System response times
- Security
- Communication protocols (custom and/or industry standards)
- Data storage
- Dimensions and weight

DESIGN SPECIFICATION

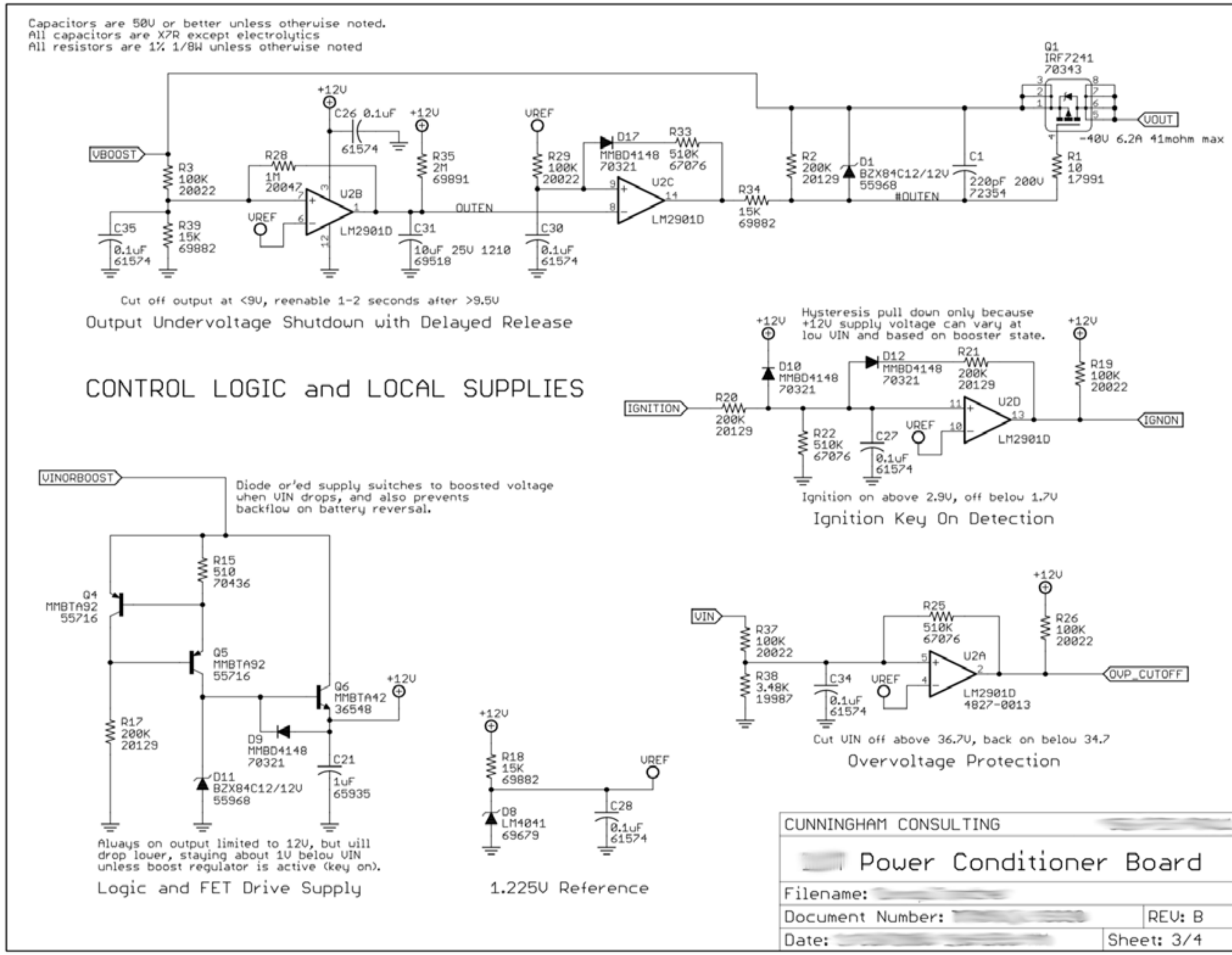
- This will allow the programmers to work more independently and efficiently: that saves time and money
- One of the most important parts of this document is the functional specification
  - It should describe how the product is expected to operate and respond to various conditions and inputs from the user or the rest of the system
  - Address possible error conditions and how to handle them.
- The design specification is often a living document, with additions and changes as the project progresses.
  - Make sure that everyone has access to the latest copy and is aware when changes are made that might affect them.
  - A version control system can automatically highlight what was changed and when.
  - Put it in writing rather than relying on verbal communications to make sure everyone is working towards the same goals.

Detailed design

Hardware Path

HARDWARE DESIGN

- The hardware engineer will create schematics (circuit diagrams) to capture the design.
- Schematics specify which components (transistors, chips, etc.) are used and how they are connected logically
- The engineer may also use circuit simulations at this stage to check and fine-tune the design, especially for analog circuits such as power supplies, amplifiers, and filters.



CIRCUIT BOARD LAYOUT

A schematic represents the logical connections in a circuit. The board layout converts that into a physical design that specifies the board dimensions, where all the parts go on the board, and the routing of the circuit traces that make the physical connections between the pins of the different chips and components.

- A printed circuit board consists of layers of etched copper traces separated by insulating substrate layers.
- The hardware engineer will specify constraints to guide the layout process.

CIRCUIT BOARD LAYOUT

These constraints are important to:

- Isolate sensitive signals
- Minimize noise
- Meet timing requirements
- Provide adequate current capacity
- Isolate analog and digital grounds
- Provide proper circuit protections (against ESD and EMI, for example)
- Meet mechanical needs such as connector placement
- etc.

CIRCUIT BOARD LAYOUT

- The **hardware** engineer works closely with the person doing the layout and checks and approves their work when done
- A **mechanical** engineer may also be involved to make sure that mounting points, hole sizes and other dimensions match up with the housing where the board will be installed
- Some layout issues may arise that require changes in the schematics, such as swapping gates or pins on a chip to improve the signal routing
  - This close interaction between the two roles often makes it easier and better to handle by the same person.
- A good CAD software ties the schematic and layout designs together
  - And handling both roles lets quickly see the issues, make decisions and changes on both the schematic and layout and keep the project moving.

CIRCUIT BOARD LAYOUT

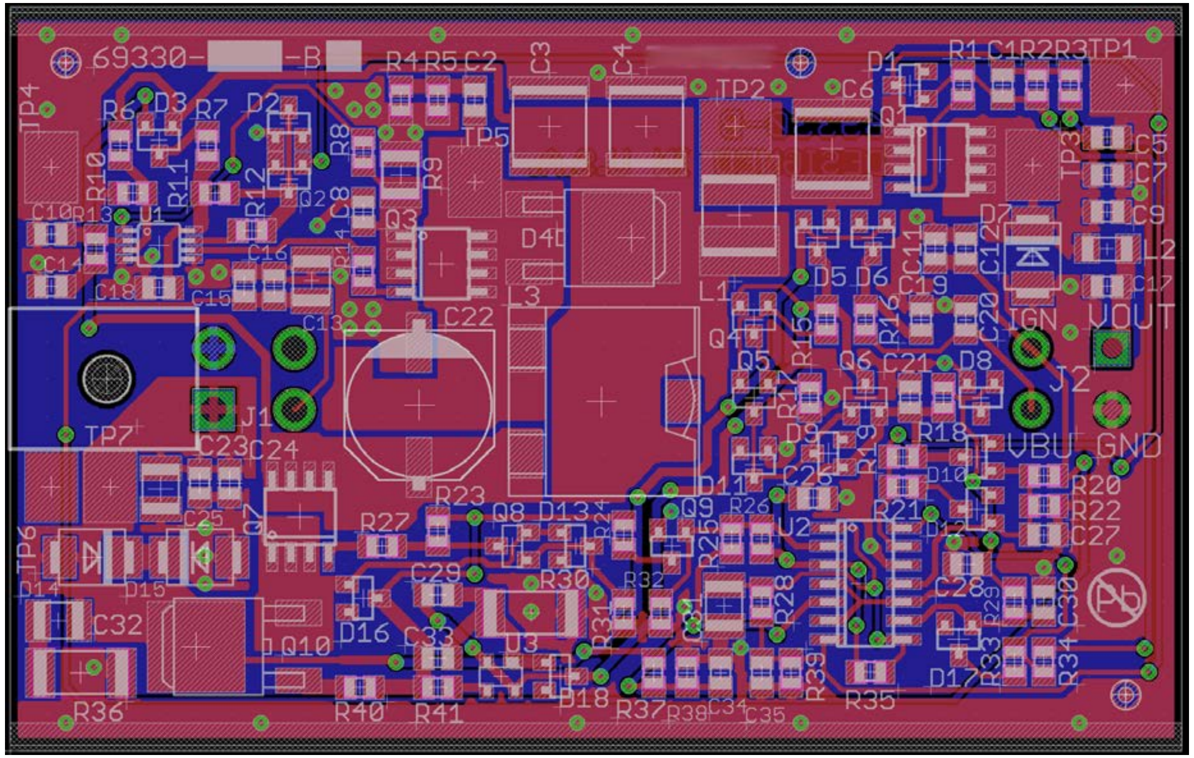
- A good layout requires the ability to visualize the signal flows around the board and to see ahead to anticipate where the bottlenecks will be so just enough space is left between the parts.
- Simple boards have just one or two layers of copper signal traces, but many if not most boards have 4, 6, 8 or more layers, like a big 3D puzzle maze
- The ability to see many moves ahead, and analyze all the alternatives, is an important skill.

CIRCUIT BOARD LAYOUT

- Each signal is routed through a board by finding the best paths between pads, components and other signals.
- A signal will often jump back and forth between different layers (using a via) in order to cross over or under other signals and parts in its way.
- Design rules are set so the software can automatically check your work and make sure the signals don't get too close to each other, to any pins or the edge of the board.
- The CAD programs can also do auto-routing, automatically finding ways to route the signals through the maze.
  - That can save a lot of time but can also create a mess if not used properly
  - I find that a combination of manual routing and auto-routing is often the best solution.

CIRCUIT BOARD LAYOUT

- Once the layout is complete, the design is ready to be turned into physical circuit boards.
- Typically a small prototype or pre-production run is made in order to test the design before committing to a larger production order, as described in the following steps.



Board layout for the schematic

BILL OF MATERIALS

- The hardware engineer will create a bill of materials:
  - listing all of the parts that will be mounted to the circuit board and any attaching cables and other devices
- For a prototype run, they will create a quick list to get the parts ordered for the prototypes.
- For production, more time is taken to match the parts with the customer's existing parts management system and part numbers.
- Alternative parts and multiple source options are also checked and approved in order to give the purchasing and manufacturing departments more flexibility.

Feasibility

- In some cases, a feasibility study is carried out after which schedules, resource plans and estimates for the next phase are developed.
- The feasibility study is an evaluation and analysis of the potential of a proposed project to support the process of decision making.
- It outlines and analyses alternatives or methods of achieving the desired outcome.
- The feasibility study helps to narrow the scope of the project to identify the best scenario.

Design Challenge

- **Time-to-prototype:** the time needed to build a working version of the system
- **Time-to-market:** the time required to develop a system to the point that it can be released and sold to customers
- **NRE cost (Non-Recurring Engineering cost):** The one-time monetary cost of designing the system
- **Flexibility:** the ability to change the functionality of the system without incurring heavy NRE cost

Design challenge – optimizing design metrics

Obvious design goal:

- Construct an implementation with desired functionality

Key design challenge:

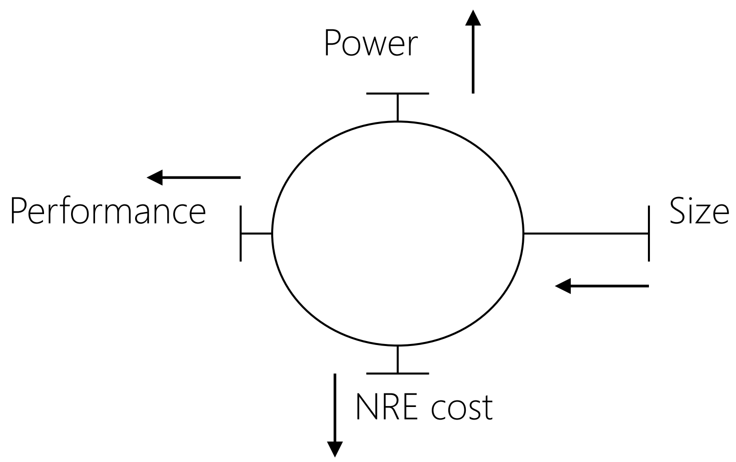
- Simultaneously optimize numerous design metrics

Design metric

- A measurable feature of a system's implementation
- Optimizing design metrics is a key challenge

Design metric competition -- improving one may worsen others

- Expertise with both software and hardware is needed to optimize design metrics
  - Not just a hardware or software expert, as is common
  - A designer must be comfortable with various technologies in order to choose the best for a given application and constraints

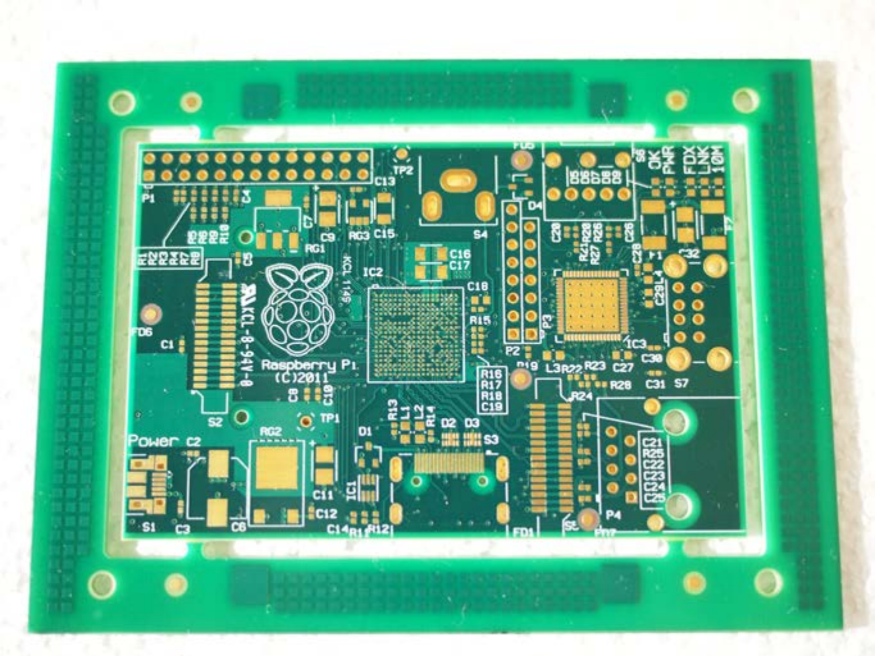


PARTS PROCUREMENT

- Your in-house or manufacturer's purchasing department is skilled at making large purchases at a low price.
- But it is usually faster and easier for us to handle the purchasing for you for a low volume prototype run.
- If I am arranging the board fabrication and assembly, I typically have the parts drop shipped to the assembly house or our technicians to save some more time.

BOARD FABRICATION

- A board fabrication house will take the layout files (mechanical drawings, Gerber files, etc.) and convert them into a physical circuit board.
- We can work with your in-house or contract manufacturers.
  - But for prototypes through board manufacturers that specialize in small runs and quick turnaround time. Example: Colcircuitos
- Automated bare board testing is sometimes used to check for any faulty boards before sending them to the assembly stage



BOARD FABRICATION

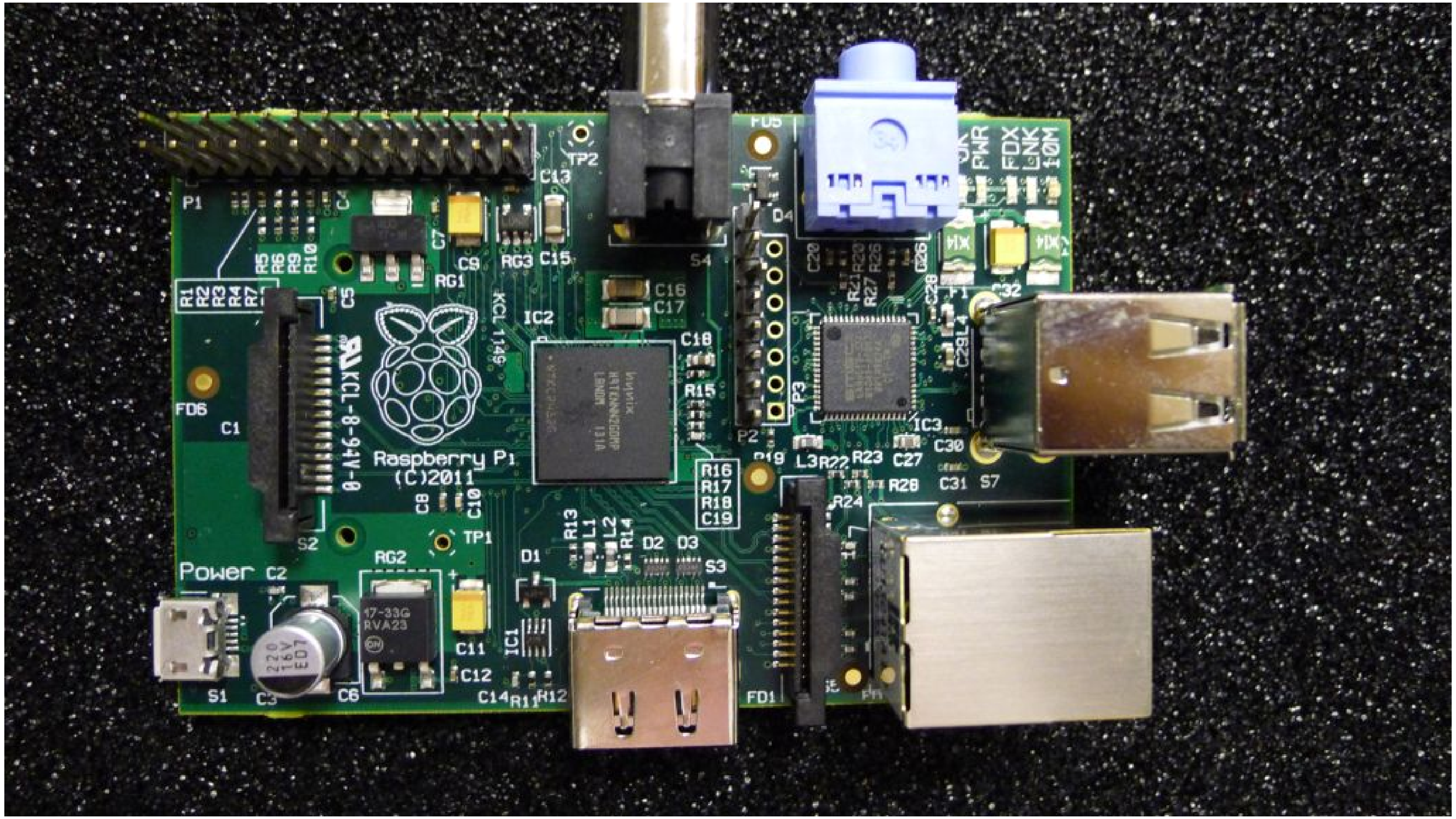
- Board faults can include opens and shorts deep within the layers of the board that may be impossible to see or repair from the outside.
- There might only be one faulty board in a batch (and usually none), but you waste valuable time if that is the one you spend a week building as your first prototype board before you find the problem.
    - Such faults are rare, but if a board has internal layers with fine or tightly spaced signal traces then the chance of faults is higher.
    - If the cost of the following board assembly (labor and parts) is high, then the small cost and extra time to do bare board testing is good insurance.
    - If the board is simple and all the signals are on the outside (1, 2- or 4-layer board) then there is far less risk if this testing is skipped.

BOARD ASSEMBLY

- Once the bare circuit boards are ready, the circuit components are mounted and soldered onto the board.
  - For surface mount parts (the most common nowadays, as opposed to thru-hole parts), a silkscreen printer deposits a shaped blob of solder paste on all connection pads on the board.
- Then a high-speed robotic pick and place machine precisely places the miniature components on the board.
- Reels of tape hold the parts to feed the machine.
- A robot arm with a tiny vacuum tube uses suction to snatch each part from the tape, move it into position, press it down and then release it.
- Each leg of the chips and components gets pressed into its own miniature dab of sticky solder paste which will hold it in place temporarily until the solder is melted in the next stage.

BOARD ASSEMBLY

- We provide the necessary files to the board assembler to create the solder paste silkscreen and to guide the robot part placement.



BOARD ASSEMBLY

- The boards then travel through a wave solder machine or infrared reflow oven (like a fancy Easy-Bake Oven) for soldering.
- Sometimes there is additional hand soldering of some components.
- Machine vision systems and humans check the boards for any misplaced or missing components.
- And electrical tests are also available to verify all the connections.
- Some electrical tests require special pads to be included in the design and layout.
- Electrical tests are sometimes skipped to save money and time on a tight prototype schedule since the boards will be manually tested by the engineer.
- They can be important for full production runs of some types of boards, however.

BOARD TESTING

- The prototype boards are returned to the hardware designer for careful testing to make sure that the design is right and that it is built properly.
- If design mistakes are discovered, they are usually fixed through a simple circuit patch
- That patch fix is either incorporated into the design of the next iteration of the boards or continues into production
    - Work at the first time? Mistakes do happen
- So testing each board is important before assembling into the final product or larger system.

PRODUCTION TEST FIXTURES

- For larger volume production, test fixtures can streamline testing, programming, and calibration of the boards.
- We will often create test fixtures, or their precursors, during the prototyping stage.
  - These can then be ruggedized and refined for higher volume production.
- These production fixtures might be stand-alone, controlled by a PC, or attached as adapters to more sophisticated generic board testers.
- They need to be designed and may involve some sophisticated electronics

FACTORY TEST AND CALIBRATION SOFTWARE

- The factory fixtures for testing, calibration, and programming will also typically need some form of software or configuration.
- You can provide that service or assist the staff or the manufacturer.
- Many boards have self-test and self-calibration procedures built-in for operation in the field

MANUFACTURING DOCUMENTATION

- Formal documents are created to record the various factory procedures that have been worked out.
- These are assembled with all the other production and design files such as schematics, layout, board fabrication and assembly files, firmware releases, etc.

RELEASE TO MANUFACTURING

- Once all the documents are in place, you will work with your manufacturing and document control departments to make sure that everything is properly recorded in the systems.
- And you will be available when full production first starts to help iron out any kinks.

Software and Firmware Paths

PROGRAMMING

- This is the bulk of the work, turning the specification into actual code in whatever programming language is used.
- Many projects nowadays use several different languages, each with their own specialty, for different parts of the system.
- The chart shows the programming, testing, and documentation phases in sequence.
  - But often it is more efficient to do a lot of the work in parallel
  - For example, you can write test code for a module or routine while or before you write the main code
  - Then you have a built-in test that tells you immediately if you have made a mistake
  - And testing small sections of code like this makes it easier to find certain bugs than trying to find the needle in a haystack of thousands of lines of code later.

PROGRAMMING

- Similarly, tools exist to allow the programmer to include bits of documentation as specially marked comments throughout the code as they write it.
- The tools then scan the code and compile the bits into a larger document.
- Future programmers can then use this document to understand the overall structure and function of the program.

TESTING

- Thorough testing is important to minimize the chances of any bug getting out to a customer.
- Testing also is used to compare the operation against the specifications and make sure that all the requirements are met, and features are implemented.
- The complexity of today's systems means that sometimes a change in one area might break something else.
- So it is often worth your time to automate the testing process to make it easy to repeat tests repeatedly to not miss anything.

DOCUMENTATION

- The programmer may scatter documentation fragments throughout the code. These can then be extracted and compiled into a master reference document for programmers.
- You may also need documentation written for other audiences such as users (user manuals), management, marketing and so forth.
- Don't forget to record ideas and plans for possible future revisions or additions to the product or product line.

RELEASE

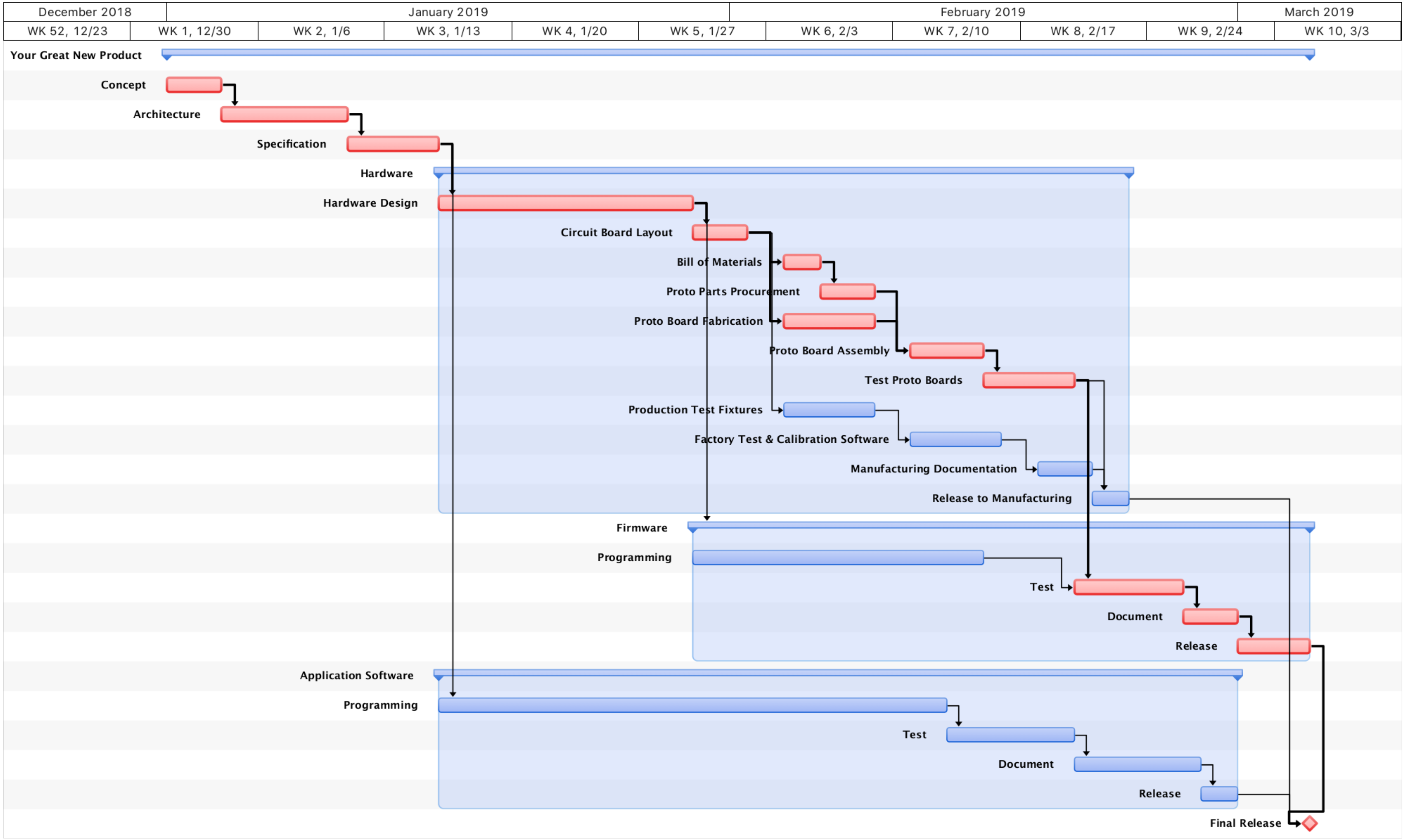
- A formal release process is important to ensure that you know exactly what was in the code at that point.
- This allows you to track changes between different versions for your release announcements.
- This allows you to go back in time to track the source of any bugs that might have been introduced.
- A release should assign version numbers and store the present state of the code into a source code management system (also called a version control system)
- Any user manuals, specification documents, and other affected documents should be revised to match the new features and functionality of the release, and then also stored in the version control system
- Record the compiler version and settings so you can fully recreate the release conditions in the future
- If there is a related hardware change, then throw in the revised schematics too.
  - This creates a time capsule of sorts for the whole project.

Final Release

- Once all the pieces are complete, and the product is out the door, you can finally wrap things up, celebrate, and prepare for the next project…

Production planning

- The production planning and tool design consists of planning how to mass-produce the product and which tools should be used in the manufacturing process.
- Tasks to complete in this step include selecting materials, selection of the production processes, determination of the sequence of operations, and selection of tools such as jigs, fixtures, metal cutting and metal or plastics forming tools.
- This task also involves additional prototype testing iterations to ensure the mass-produced version meets qualification testing standards.


December 2018
January 2019
February 2019
March 2019
WK 52, 12/23
WK 1, 12/30
WK 2, 1/6
WK 3, 1/13
WK 4, 1/20
WK 5, 1/27
WK 6, 2/3
WK 7, 2/10
WK 8, 2/17
WK 9, 2/24
WK 10, 3/3
Your Great New Product
Concept
Architecture
Specification
Hardware
Hardware Design
Circuit Board Layout
Bill of Materials
Proto Parts Procurement
Proto Board Fabrication
Proto Board Assembly
Test Proto Boards
Production Test Fixtures
Factory Test & Calibration Software
Manufacturing Documentation
Release to Manufacturing
Firmware
Programming
Test
Document
Release
Application Software
Programming
Test
Document
Release
Final Release

Embedded Systems

“Dortmund“ Definition: [Peter Marwedel]

Embedded systems are information processing systems embedded into a larger product

Berkeley: [Edward A. Lee]

Embedded software is software integrated with physical processes. The technical problem is managing time and concurrency in computational systems.

Definition: Cyber-Physical (cy-phy) Systems (CPS) are integrations of computation with physical processes [Edward Lee, 2006].

WIKIPEDIA
The Free Encyclopedia

An **embedded system** on plug-in card with a processor, memory, power supply, and external interfaces. An embedded is a controller programmed and controlled by a real-time operating system (RTOS) with a dedicated function within a larger mechanical or electrical system, often with real-time computing constraints

Starting point: “Microcontroller System Design”

- Hardware design
  - Evaluation hardware boards
  - Reference schematic circuit
  - Application notes
- Software
  - C compiler, assembler, and tool chains
  - Example codes, modular, and flowchart
- Debugging Tools: emulator, JTAG programmer