The PhD Thesis Deconstructed

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Helping students wandering in the land of the mind to work, finish, publish, become famous, have impact, win prizes, and reflect glory on their thesis advisors

Figure 1. Thesis committee.

Editors' Note

Stuart Card recently chaired the Dissertation Award Committee for the IEEE Visualization Pioneers. In that role, he read more than two dozen visualization dissertations, and he previously served on numerous dissertation committees. This article is based on his well-received talk to the Pioneers of Vis 2015. PhD students who hope to write an impactful dissertation that might someday be described in this section: read carefully!

I've been asked to talk about the factors that contribute to a prize-winning, impactful thesis on visualization. There are many better qualified experts than I on this topic. That said, I have recently had occasion to read a good number of theses in this area and couldn't help noting that the same issues tend to arise in multiple dissertations. So I thought I would share a few observations about these, not so much as a qualified expert or member of a thesis committee (see Figure 1), but more in the spirit of the farmer neighbor down the block who might help you with your prize tomato entry. I have divided my observations into three parts. First, as befits my training in human-computer interaction, I start with a brief task analysis and try to answer the question, "What's the point?" Then I derive a set of design requirements to answer the question, "What makes a thesis great?" Finally, I get to the issue of execution: "How do you actually get it done?"

But, wait, there's more! Several years ago, John Perry Miller, the dean of the graduate school at Yale University, wrote a charming little book entitled *Creating Academic Settings: High Craft and Low Cunning* about how he shaped the graduate school academic environment at Yale, despite the aid of several of his colleagues.[1] I have always admired this book for its frank admission that the birth and husbandry of institutions for higher purpose requires both inspiring vision and skilled over-the-board pragmatic play. Mostly my observations are about the high craft aspects of thesis writing. But I thought it might be useful, and you might even enjoy it, if I stuck in some of the low-cunning bits too. I have tried to do this, appropriately labeled, so you are fairly warned about the slightly wicked parts.

What Is the Point of a Thesis?

Let's start with the deconstruction. Why should anyone ever be required to take three years out

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of her or his life to write a book that will only be read by five people? In response, I would argue there are at least four good points, four beneficial transformations that come out of writing a thesis.

A thesis is the entry ticket into the club.

This is where you finally get to enter into the profession to which you have long aspired and to exercise the promised "rights and privileges pertaining thereto." For example, you get to wear your hood to work and have an airline stewardess call you "doctor." Even better, you get to march in the parade (see Figure 2).

Actually, this parade deserves a moment of reflection and even spiritual reverence. The parade is expressing continuity with 800 years of scholarship that flows from the establishment of the great European universities, within whose walls the preparation of a dissertation played a major part. We're talking here about the thesis as a central method for the creation, accumulation, and transmission of knowledge and our civilization itself. As they complete their theses, current PhD students acquire standing to join as principals in that great enterprise. This observation leads to the second point of having a student write a thesis.

A thesis is the blunt means by which, and the certification testifying thereof, that the student has become a professional.

The transformation I have in mind here is a bit more profound than you might presume. To me, a professional has two magical abilities. A professional can

- Create order out of chaos.
- Do it on schedule.

When you ask a question within her professional expertise, a professional always comes back with an answer. Of course, the profundity of the answer may likely depend on the resources available, like time—and, of course, the fee. There is no free lunch. But if a question is within her professional domain expertise, a professional can always produce some kind of answer.

Question: Do leprechauns exist?

Answer 1: (response time 15 sec., fee $15): "Not in my opinion."

Answer 2: (response time 1 year, fee $1 million): "66% of first-year students say yes, according to a survey of likely voters and a diary study, but we were unable to produce one in the laboratory."

Figure 2. Academic processionals. (Courtesy of University of Glasgow Photographic Unit)

So a professional can always answer an expertise-relevant question, but what *really* makes you a professional is being able to produce an answer on schedule, as well as producing that answer independently of how you are feeling that day.

At the master's level, the professional learns how to apply the methods of a discipline and can execute them skillfully to do a job—to give that answer. With the PhD, we go beyond codified methods and let the student in on the dark, whispered secret of the universe that behind the pulled-back brocade curtain of the known, lies a universe of rank, snarling disorder and chaos.

Think of a PhD professional, her desk surrounded by a little potential energy well of lower entropy relative to the universe, the air cooler, even brisk. Her job is to reduce entropy for others as well by inventing methods, algorithms, and theories usable by them to create order out of chaos. I realize this definition is a bit aspirational, but I still defend the idea of the professional and the notion that the thesis serves as the blunt instrument of this transformation—or of selection.

A thesis is the student's cognitive toolkit and provisioning.

The thesis results in the internalization of the literature, tools, methodology, and work methods for one topic, and a list of future ideas—all of which will be the basis of the student's competitive advantage over the next five years. If done properly, the student, having spent four to six years thinking and learning about the literature and the methods for his or her area, has a small domain where she or he is the smartest person in the room. A corollary to this proposition is that it might be a good idea to plan out the domain for which you actually want to be so knowledgeable. Begin with the end in mind.

A professional knows her tools.

Nothing is more important than this observation, which is possibly implied in last point, but I think it is so extremely important that I give it its own reflection. Professionals always know their tools extraordinarily well and take care of them. It's not enough to know MatLab. If you are going to use it as one of your main tools, you have to be a MatLab whiz. It's not enough to know how to compile C for a Cranberry Pi. If doing so is part of your professional kit, you should know about the cases where the compiler compiles bad code because of system initialization assumptions when compiling to bare metal. Mastered tools give you superhuman powers. In planning the thesis, therefore, it might be useful to make a short list of the tools in which you desire whizification and plan the thesis to contribute thereto.

What Makes a Great Thesis?

So this is my deconstruction of why a thesis is properly a part of a PhD program, but now let's approach the beast itself. What are the special properties that make a thesis great?

Good Song Choice

The mere choice of topic for a thesis tends to put a ceiling on its potential interest and impact. Like the singing contests on television, the content sometimes matters as much as the performance. We once had a Nobel Laureate come talk to us about his ideas for how to do research. His surprising number 1 recommendation: Don't work in an area that doesn't have good funding.

You are going to put in a lot of work and be examined on something hard, but most students have some influence over what that something will be. Why not choose something that for the same effort makes success more likely? Why not choose something that for the same technical success has wider impact? It helps to choose an area where there are big rocks that are still in the ground waiting to be discovered and where you will have access to resources for finding them.

Original

Topics that are original, that ask new questions, tend to do better. What does it mean to be original? If you were going to measure originality on a scale, a possible scale might look something like this:

Originality1 = $\log_{10}$ (*years-before-someone-else-would-have-invented-it*)

You can often find topics likely to have a higher *Originality1* index by looking for new technology that is emerging near you—that is, where you can get to the future before they can. Here's the relevant principle of low cunning:

> ***Low-cunning point 1:*** Look for an unfair advantage

Technology that is emerging and to which you have privileged access is ideal. For example, it was relatively easy to do original work on the mouse pointing device[2] by being nearly the only people on Earth with access to a mouse.

Impactful

The sober way to look at impact is to trace what led to what, years after the fact. Unfortunately, this technique has almost no planning value. But here's an outrageous shortcut: given a thesis topic, imagine what the impact might be. For this purpose, imagine we had another scale that distinguishes between barely felt perturbations and advances that shake a field to its foundations. It is admittedly fanciful, but there is an obvious scale developed to measure impacts based on easily observed effects: the Modified Mercali Intensity (MMI) scale for earthquakes. Let's have some fun and apply it here.

By convention, MMI scale numbers are given in Roman numerals to separate this experiential scale from other physically measured scales. Those Roman numerals can be roughly coordinated with the Richter scale, as in Table 1. I have simplified the overlaps in the seismic scale of innovation (SSI) version of this scale.

Although fanciful, I am struck by how apt the descriptions sometimes are:

- A minimal thesis that barely squeaks by would have an impact of 1.0 ("not felt, but recorded"). I know theses like that.
- A thesis with an interesting new idea might get a 5.0 ("sleepers awake").
- A major scientific discovery would get a 7.0 ("serious damage, rails are bent, general panic, partial collapse"). Isn't that just what every graduate student dreams will be the impact of her or his thesis on the field?

Imagine a half dozen completed theses in your area. Estimate SSI scores for them. These will serve as anchors. Now estimate the SSI for the thesis

Table 1. Seismic scale of impact.

Phenomena	MMI*	Richter	SSI*	Characteristics	Number/year
No earthquake	0	0	0	Clone	
Not felt, but recorded	I	0–1.9	1.0	Reimplementation of existing technique to similar problem	4,000
Hanging objects swing	II–III	2.0–3.4	2.0	Application of existing technique to new problem or minor additions to technique	830
Felt by some, like a passing light truck	III	3.5–4.2	3.0	Nonobvious use of existing techniques	170
Felt by many, dishes rattle	IV	4.3–4.8	4.0	Refinement of existing paradigms by substantial new invention	36
Felt by all, sleepers awake	V–VI	4.9–5.4	5.0	New idea for minor component	7.5
Slight building damage, books fall, liquids spill, windows break, walking is difficult	VI–VU	5.5–6.1	6.0	Discovery of new major component	1.6
Considerable building damage, chimneys fall, some houses	VIII	6.2–6.9	6.5	Trendsetter, imitated by others	0.66
Serious damage, rails are bent, general panic, partial collapse	IX	7.0–7.4	7.0	Course change for industry	0.32
Great damage, masonry buildings destroyed, bridges fall	X	7.4–7.9	7.5	Major paradigm shift	0.13
Damage nearly total, most works of construction destroyed	XI–XII	8.0	8.0	Restructuring of field (examples include Sketchpad, Smalltalk, and Star)	0.067

**Modified Mercali Intensity (MMI) scale, seismic scale of innovation (SSI).*

topic you are considering. Try a couple other topics of interest. This exercise should at least get you thinking about the relative impact of your ideas.

Presume that you have finally figured out a thesis topic that could shake up the world. Despite the clever ideas it will surely contain, people must still be able to read and understand it, and they must be motivated to do so. This observation leads to the next property that makes a thesis great.

Well Written

A great thesis is a page turner. Readers can't wait to see what's next. Furthermore, after reading a great thesis, the reader should be able to remember and to restate it. Compare this ideal to the reality of many theses in which a swamp of complicated results have trouble settling into an organized whole.

Actually, for this specific case, our department of low cunning does have a trick:

> ***Low-cunning point 2:*** Restate significant results three times: once for your mother, once for an intelligent graduate student friend in the Art History Department, and once for a member of the thesis committee.

Because meaning is conveyed in writing by adding layers of detail onto description, the detail doesn't come across as redundant, but rather, it builds. Imagine you are writing the thesis in the following made-up example and you are about to announce your results. Using this technique, a thesis might be stated this way:

- "Does this visualization enable us to find the bottlenecks slowing down the visual search task? The answer is 'yes.'" [This is the statement of the results for your mother.]
- "Visualizations having a low entropy score on their recurrence plots were 36 percent faster." [This is the statement for the intelligent art history major.]
- "This result was significant when corrected for Dolby's second index of cognitive heteroheroic shrinkage, $F(1,112) = 5.79$, $p < 0.025$." [This is the statement for a thesis committee member.]

Each of these statements adds more detail about the same result. The student's mother is a stand-in for any non-technically trained but intelligent reader. If your mother is dean of engineering, imagine someone else like your favorite Uncle Bobby. The point is that this technique also makes the thesis more readable, even for the thesis committee expert. The initial plain English statement can be used to build a strong structure for the overall thesis. For example, these results might be in a section titled "Bottlenecks," echoing a term from the mother's statement of the results.

I have drawn out this point because the single greatest problem in student thesis and scientific article writing is the lack of a clear and easily perceived structure that marshals the data and marches the argument, tugging the user along. The low-cunning expedient of restating the results three times and reflecting a general statement into headings can often do wonders (and quickly) to sharpen a thesis that has lost its way perambulating the winter gardens of philosophy or rutting among the weeds of statistics.

Since we seem to have landed briefly in the general writing department, this is a good place to point to a few unconventional sources that focus on writing, not so much as the construction of a document, but more as the orchestration of interactive, moving idea-parts.

In "Writing the Empirical Journal Article," Daryl Bem, a professor of psychology, uses a cognitive model of the readers' mental work to guide the author's writing choices by loosely simulating the effect on the reader.[3] Bem's chapter is where the suggestion for stating results three times comes from. Francis Christensen and Bonniejean Christensen developed a very compatible theory and method of writing that shows why Bem's suggestion works.[4] This method was first stated by John Erskine in an essay that is worth quoting:

> The principle is this: When you write, you make a point not by subtracting as though you sharpened a pencil, but by adding. When you put one word after another, your statement should be more precise the more you add. If the result is otherwise, you have added the wrong thing, or you have added more than was needed.[5]

This is subversive advice, since the standard Strunk and White rulebook[6] advises students to write with nouns and verbs and not with adjectives and adverbs, whereas Erskine advises, "What you wish to say is not found in the noun, but in what you add to qualify the noun." The Christiansen method allows the expression of complicated ideas by layering various sorts of phrases to build up the meaning. To support the Erskine-Christiansen view, the Chirstensens provide evidence that many famous writers use this technique.

Finally, John Carlis, a professor of computer science at the University of Minnesota, suggests treating complex writing projects like complex software projects.[7] Using these methods, he claims a student can write a thesis with little or no backtracking. All these references aim to improve your ability to express complicated ideas and increase your writing speed by articulating the patterns underlying the structure of the text.

I see we've overstayed our visit to the general writing department. This might be the appropriate moment to shift departments and think of a thesis as a set of ideas we would like to propagate and grow in many minds and many places.

Packaged to Travel

Great theses aren't just read, they *infect*. They inject seminal ideas, which grow and take over the host's brain, ultimately going viral as they spread into other hosts. From the point of view of the thesis writer, this desirable state of affairs is called impact. From the point of view of the thesis writer's advisor, this desirable state of affairs is called tenure. It pays to give careful consideration to packaging your ideas and results so that they are self-contained and can be transported into another context, where they can combine with other results. This is one of the mechanisms by which science cumulates. There is a low-cunning way of stating this principle:

> ***Low-cunning point 3:*** People basically read your paper to write theirs. Your ideas are more likely to spread if you help out.

Figure 3 gives an example of a set of ideas packaged to travel. In this case, a summary of information visualization systems as defined by their transformations has been packaged into a compact diagram.[8] Subareas of information visualization can be explicated in terms of transformations in this diagram. Puzzling phenomena can be explained, like the fact that identical-looking displays can reference different system states, as when a data item being deleted from the display could mean it is deleted from the database or just hidden by a visual transformation. The rest of the figure shows this transit strategy actually working. The basic diagram is reused directly in Jeremy Boy's thesis[9] and indirectly in Huron's thesis[10] via an article by Cottam.[11] In this case, these reuses of the diagram improve on the graphics of the original or combine the original with new concepts.

How Do You Write a Great Thesis?

Now that we have some idea of what a great thesis is, it's time for some observations about the hard work of actually constructing one. Ideas alone are cheap; it's the execution of those ideas that counts. Here I've collected a set of suggestions that I find myself making repeatedly to thesis writers. These generally try to help bridge the gap between the intellectual world of ideas partially glimpsed and the concrete world of actual physical deliverables.

Plan the thesis like a collapsible telescope.

Give the thesis a tactical plan. The first section of the telescope should be something that you are sure can be done with relatively low risk in relatively little time, but that will still produce an ac-

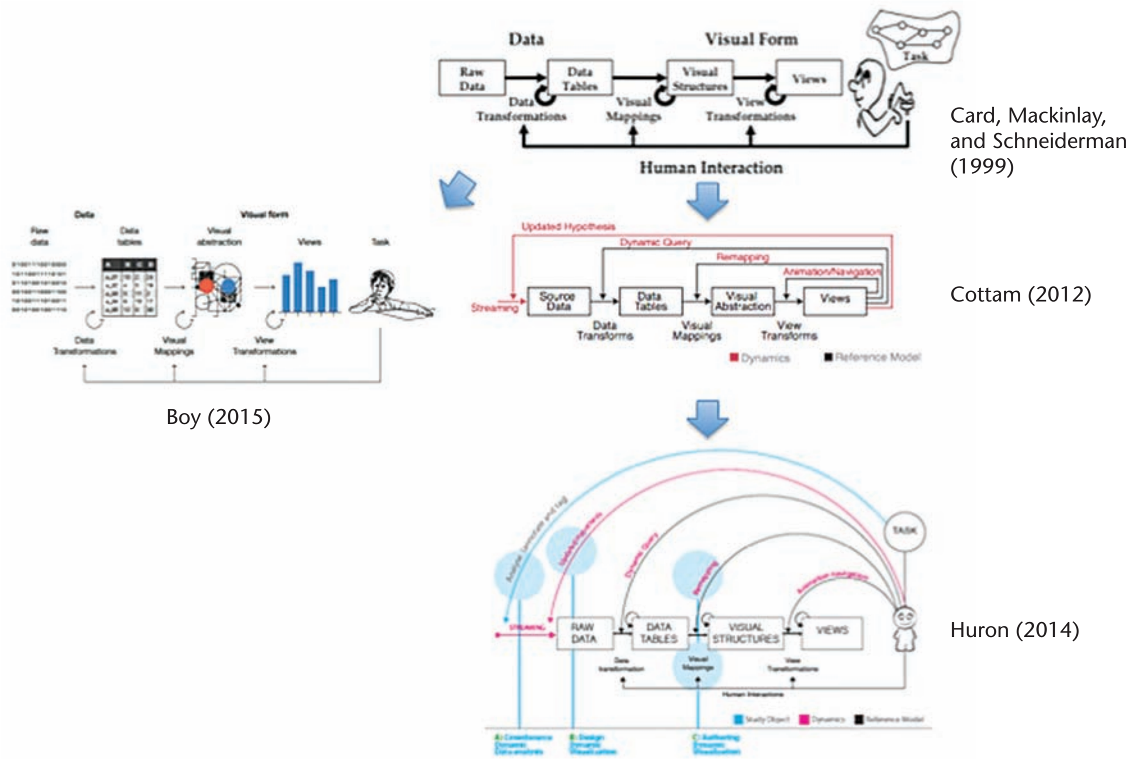

Figure 3. Propagation of ideas packaged to travel. The diagram helps explain puzzling phenomena, and in fact, the reuses of the diagram improve on the graphics of the original or combine the original with new concepts.

ceptable thesis. The telescoping sections extend for additional accomplishments (but also more time and risk) until you either finish what you set out to accomplish or run out of time.

Several times I've seen students with ambitious plans for the Great American Thesis reluctantly accept the telescope plan, later to find themselves in the position of only being able to accomplish the first or first two sections of the telescope; yet they come out of the process with excellent theses. Had they gone for their original plan, they might not have done so well.

Another way of putting the point is that a project has basically four variables that trade off against each other: time, cost, quality, and scope. The telescope metaphor sets up the project so that if it runs short on time, the project absorbs the hit in reduced scope instead of reduced quality.

It's okay to let the thesis have one hard thing that you're good at.

If you want to demonstrate virtuosity, it's okay to plan in one part that other people would find difficult, providing you have some experience and justified confidence that it will succeed.

> ***Low-cunning point 4:*** It's okay to plan in one difficult part, but not two.

One hard part within the student's skill set helps to make the thesis unique. It keeps out the riff-raff. But, two makes the risk too high.

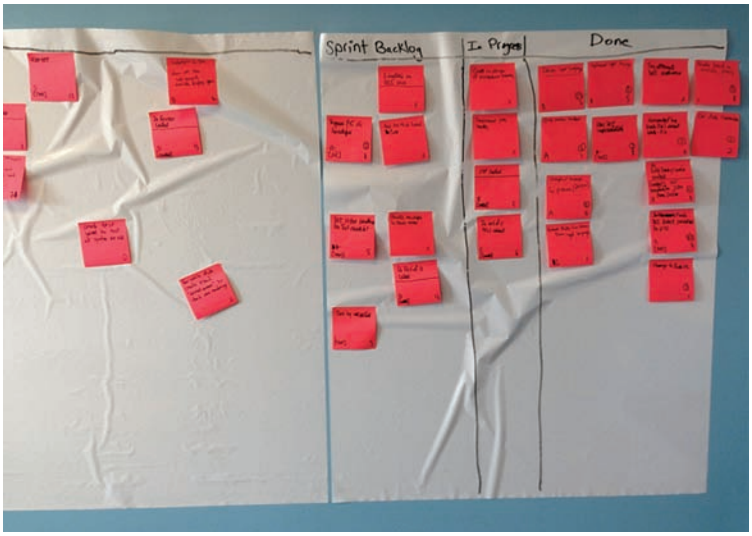

Figure 4. Simple management scheme. The large visual can help students estimate task times and make local decisions against a larger context.

Adopt a simple management plan that divides the thesis into parts.

With malice aforethought, a thesis is a project at a larger scale than can be handled informally, unlike a conference paper or a journal article. To succeed, the student needs to discover and adopt some simple management scheme.

Figure 4 shows an example scheme built loosely upon notions from scrum and agile software development. Work in this scheme is a series of sprints, typically one or two weeks long and typically aligned with the development of some deliverable

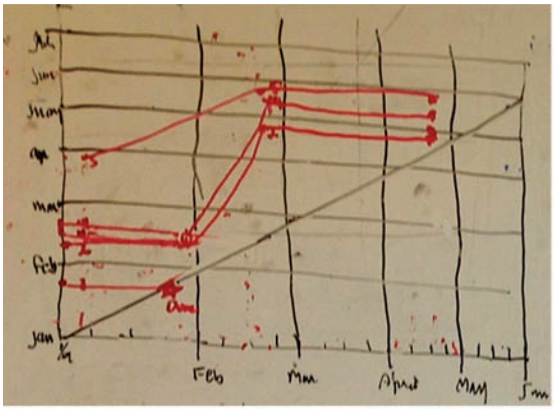

Figure 5. Maintaining overall control of the timeline. Breaking the thesis into major tasks allows the student to track date promised versus actual date completed.

feature or other tangible focus. During the sprint, the goals stay constant, providing day-to-day stability. The tasks needed to accomplish the sprint are written down on Post-it notes along with an estimate of how long each will take, expressed relative to other tasks as (I love this part) Fibonacci numbers. The scheme works particularly well if you use large write-on cling polyester sheets to hold the Post-it notes. These easily cling to the wall (where they stay safely disentangled from whiteboard use or piles on a desk and can be written on with dry erase markers (with no damage to the wall). Divide the sheets into sections, such as "backlog," "in progress," and "done." At the end of the sprint, the plan becomes flexible and is updated for the next sprint. The Post-it notes are moved appropriately. This encourages you to make local decisions against a larger context, yet the plan is changeable. To help estimate task times, the actual task times are recorded on the Post-it next to the previously estimated times, and these are fed into a regression, which produces a more realistic time estimate based on actual production measurements.

A method for maintaining overall control of the timeline is to break the thesis into major tasks and estimate the date when each will be finished. It is important that these be your own estimates and not be dates you were forced to accept. Figure 5 shows a sample that tracks date promised versus actual date completed. New estimates are made periodically (such as during your weekly advisory session). The estimates are connected with a line.

Perfect estimation would lead to a set of horizontal lines that traveled across the chart diagonally. The lines in Figure 5 are more typical; after four months of work, some tasks that were 2-1/2 months from completion are now four months from completion. In fact, a few tasks are likely to be parallel with the diagonal, indicating that they stay a constant time away from completion. This phenomenon will be familiar to thesis supervisors, but it is often a surprise to the student. Because the estimates come purely from the student, there is no escape from a natural teaching moment.

Structure time to optimize intermediate long-term working memory.

Time is precious. Like gold or diamonds, it must be mined from the environment. But unlike gold or diamond, time interacts with everything in the environment, rapidly oxidizing into flaky, irregular, minutes-sized pieces. The chlorine gas of time is interruptions. Interruptions cause time to interact more strongly and with even more of the world, oxidizing into task-avoidance errands, unnecessary video-game skills, and even ordinary table salt.

Thesis writing is an example of what is sometimes called *deep work*—that is, work involving a lot of knowledge linked together in complicated ways, as opposed to shallow work, like answering email. In deep work, the really important thing is the ability to keep track of an immense amount of knowledge and relationships and scraps of knowledge and relationships, some of them inconsistent and even contradictory. The idea is to get the biggest amount of relevant knowledge possible into your "mental space" where those magical associations and visual imaginings can happen. Helter-skelter interaction of time with the environment pulls against the capacity to do deep work.

You have a kind of memory, different than the more widely known short-term and long-term memories, sometimes called *intermediate long-term memory*[12] (https://en.wikipedia.org/wiki/Intermediate-term_memory). ILTM extends from minutes up to a few hours, days, or even weeks, according to different researchers, during which time it either consolidates into long-term memory or is forgotten. This kind of memory is much less studied than other kinds of memory, so I have to speculate some, but it seems pretty clear that in deep work, such as writing a thesis chapter, there is a lot to remember—ranging from "Where are the parts of that figure stored?" to "Just what quantitative analysis methods have been used for recurrence analysis and how do you calculate them?" If you don't pay attention to these details, they seem to fade. Furthermore, repeated use of this memory seems to aggregate the elements of memory into larger "chunks."[13] After working with it for awhile, you can remember a particular reference and the results in it as well as other references by the same author all together at the same time. A few days later though, some of the parts will have faded.

This suggests there's a benefit to working in larger time blocks. It is important to realize that not all or even most of the memory has to be in the head. The things to be remembered are partly in the head, partly in notebooks and on whiteboards, partly in other people, partly generated by visualization software. That doesn't change the basic problem. Because there is so much to remember, optimizing the use of ILTM can make a big difference because of the amount of information then available and the chunking phenomenon. The more the elements of ILTM are used, the greater amount of the information that consolidates into long-term memory.

Here are three ways to organize your time so as to optimize ILTM for hourly (hyperwork shots), daily (four-hour thought blocks), and sustained deep work.

Hyperwork shots. At the hourly level, trying to work on a thesis while facebooking with friends, checking email, and bantering with your office mates makes it hard to have a large enough block of time to get anything going. If we could see into our ILTM, it would probably reveal a miscellany of memories taking up space. But just working continuously is hard to motivate and to sustain. The following technique, hyperwork shots, was taught to me by one of my professors many years ago, although it is constantly being rediscovered. It is based on the notion is that just about anybody can stand to work hard for an hour, if they are prepared for it. The method is simple:

> ***Clear the Decks***: Get your coffee. Make that telephone call. Visit the restroom. Buy that clotted cream scone. Decide on the piece of your thesis work you are going to try to do during this step.
>
> ***Start the Clock***: Set a timer for 50 minutes.
>
> ***Work***: Work intensively (hyperwork) for 50 minutes. No talking. No using the restroom. No getting new coffee. No anything. Just work! After all, it's only 50 minutes. And anyone can work for just 50 minutes.
>
> ***Repeat***.

The hyperwork shot method is sometimes called the Pomodoro Technique because, apparently, some people, for unknown reasons, think the method goes better if you execute it using kitchen timers in the shape of tomatoes. The reason for choosing 50 minutes is that with a 10-minute rest, one cycle fits into an even hour, allowing you to cascade cycles and also to neatly slot them into your calendar. Even without doing that, many people have noted that they get a day's work done with just two hyperwork shots. The reason isn't only because of the reduction in distractions. In an hour, I think you are already starting to build larger and better-linked structures in ILTM.

The deep work of writing a thesis must be integrated into the rest of your life, yet still provide the conditions that generate large and complex ILTM structures.

Four-hour thought blocks. It pays dividends to set aside large uninterrupted work blocks for working on a single project. This is especially true for blocks of four hours. Optimally, this could be four hyperwork shots. Four hours is a number that seems to pop up often. Neil Stephenson, the author of the science fiction novels *Diamond Age* and *Snow Crash*, claims that he is by far more productive when he has an uninterrupted block of four hours and that two blocks of two hours each is much less productive. My guess would be that four hours allow him to build much more efficient ILTM structures that include larger chunking patterns. Productivity seems to increase nonlinearly with these larger time blocks, at least up to four hours.

Incidentally, working on two different deep work projects at the same time can cause interference. My experience suggests that it takes about four hours to shift from one such creative project to another, and then four hours to shift back.

The Zen of sustained deep work. The deep work of writing a thesis must be integrated into the rest of your life, yet still provide the conditions that generate large and complex ILTM structures. This method derives from the writing method Don Norman (University of California, San Diego) used to write more than 20 books and which he teaches his students. Just as the four-hour thought blocks can be thought of as a way to effectively integrate four-hour hyperwork shots into a larger structure, the Zen of sustained deep work method is a way of integrating four-hour thought blocks into an even larger structure:

> ***Rise Early***: Rise early (5 a.m.).

> ***Unplug***: Decouple from distractions. Unplug the Internet.
>
> ***Work:*** Work three to four hours, or as long as you can.
>
> ***Prime the mind:*** Do this *every day*. It takes two weeks of this discipline to prime the mind before there is any progress.
>
> ***Sustain the discipline:*** If you *miss even one day*, the two-week clock starts over again.

Notice that if you are a professional writer, you have to more or less sustain this discipline for life. Notice further that although some days will produce more than others, even a relative off day might produce two pages, which extrapolated annually, would be 700 pages of output for the year. When it's working, the method should produce a stream of ideas, including in the middle of the night.

I would claim that part of the reason this method works is that ILTM continues to build up across days based on the observations that it takes about two weeks to build up to the threshold for taking on really difficult deep work and that the structure built is so fragile. Remember, we are talking about tasks that are difficult, in fact, perhaps at the edge of your capability. Because they are so hard, they require marshaling discipline and mental resources. When Newton was asked how he discovered the universal law of gravitation, he replied, "By thinking on it continually. I keep the subject constantly before me and wait till the first dawnings open slowly, little by little, into a full and clear light." In other words, his answer was the same as Norman's.

Start reading the literature early.
Knowing the literature in your area is such an advantage that it is puzzling why it often isn't started earlier. It is sometimes said that it is good to form an independent approach before falling into the same approach as everyone else. There is some merit in this argument—for, say, two weeks. On the other hand, it could be nearly fatal to discover from your paper's reviewers that your cool, independent approach is indeed cool, but was done five years ago by someone else.

It's hard to appreciate how vastly cheaper it is to find literature today than a few years ago. Imagine what it was like to actually have to physically travel to a library, to physically turn the actual pages of bound volumes of literature indexes and wander through wooden trays of paper cards to find a possible reference, physically tiptoe with quiet feet off to the stacks, search for the bound journal, read, and take notes by hand. And that's when things went well; researchers often had to shuffle among different libraries to find a copy or depend on an interlibrary loan.

Now, in a single coffee, you can locate 10 to 20 references and download PDF copies. Applications let you store and organize this literature. Notebook programs let you take notes and automatically find related literature. The point is that you can put this drop in research costs to your advantage. You can try to build up an analytic view of the literature and its shortcomings. This view of the literature can be of enormous help in designing your studies and giving the rationale for your thesis. It's the knowledge that keeps on giving.

Make the scaffold disappear.
The presentation of a thesis should have structure, but often too much of the scaffolding by which this structure was achieved is left in place and it overwhelms the content—how a section fits into the whole, what it's going to do, and how it did it is elaborated with such earnest, didactic detail that all you can see is scaffolding. Structure is good, but good structure is invisible.

Don't explain away your great result as noise.
There are sometimes effects in the data that do not come out as predicted, and students are often tempted to explain these away as noise, stupid subjects, or whatever. Actually, a phenomenon that is strongly predicted but doesn't work can be a gift from the Thesis Gods. This is the way most discoveries start and should be handled carefully. I have seen at least two occasions where theses dismissed as noise discoveries that their authors should have made. You can't dry-lab nature.

Finally we come to the end. Theses have a long tail. It's hard to make them end. The best advice I can give here is Michael Faraday's reply when a young aspirant asked him the secret of his success as a scientific investigator. Faraday answered, "The secret is comprised in three words: work, finish, publish." Write that on your whiteboard or nail it to your door. The result may be a prize thesis, or at least one with impact.

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