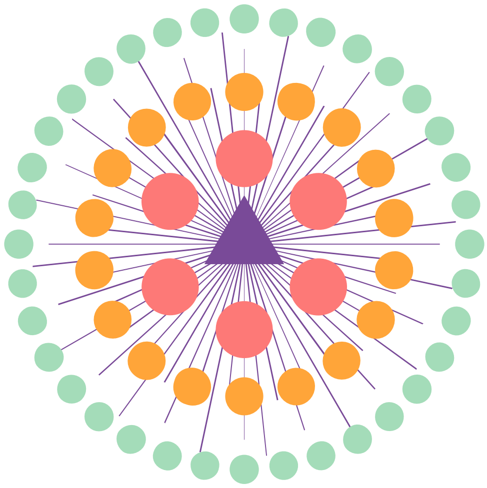
A Collaborative Spaced Repetition Learning System



Learning Technology & Digital Entrepreneurship E17, DTU

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Abstract

Students forget the vast majority if the things they learn during the course of their education. Research have shown that it is possible to memorize information into long-term memory in a time-efficient manner using active recall and spaced repetition. I propose a collaborative learning platform to facilitate co-creation of notes and flashcards. I explore possibilities for integrating course notes and flashcards in one format to avoid content duplication. In this software, students would be able to comment, suggest changes and flag flashcards in need of verification by the class and the instructor(s). I propose a scheme for auto-tagging user created content based on a knowledge graph from Wikipedia, which would allow related flashcards to be identified, and could give more meaningful flashcard review sessions and an automatic level of organization. In addition to the flashcard format, the students are also able to share snippets of "insights" or "highlights" from books, lectures and web resources etc., as summaries of what they thought was the essential take-away points for the given topic. The top-performing students can thus act as a TA for the whole class instead of helping just their closest group of friends.

This system allows the individual student to see what the class collectively perceived as the most important information in summarized form, and reach a greater understanding for themselves. It is not a substitute for individual effort, which is always essential for deep and lasting understanding. It is an aid to understanding *during* the learning process, and to memory retention of the core material *after* the learning process. The sharing of insights and flashcards enables a class of students to leverage each others understanding, and create flashcard material to use for exam preparation and the future beyond.

Contents

1 About me

I am a MSc student in Mathematical Modelling and Computation at DTU (Technical University of Denmark). My main topic of interest of machine learning, deep learning and artificial intelligence, as it applies to a broad field of applications. This field field is about teaching machines to identify patterns in data in order to perform tasks that have been very difficult for machines traditionally.

1.1 Motivation & Area of Interest

About a 1.5 years ago I developed an interest in how humans learn, learning efficiency and especially techniques for enhancing long-term retention. This came out of a frustrating realization that I only remember a small fraction of what I learned on my Bachelor degree in Physics and Nanotechnology. It turns out that using spaced repetition, it's actually possible to remember a much higher fraction of learned material with relatively small effort - at least in theory. This is possible due to the method of *spaced practice*, where the average time between recall sessions of information increases faster than linearly. Intrigued by this possiblity, I experimented with using Anki, a spaced repetition software (SRS) in the fall semester of 2016. Ultimately I found it too time consuming and I had other problems with it (which I will detail later), so I dropped it mid-semester. I still thought it was a fundamentally good idea that just needed better implementation of flashcard organization, user interface and ease / speed of use.

I took the course "Learning Technology and Digital Entrepreneurship" to get inspiration for this spaced repetition software idea and to get an introduction to various learning theories. It would also give me the opportunity to read up on the latest on mathematical models of human memory and spaced repetition.

After my first very rough prototype I developed during the course (see Appendix A.2) I realized that the software platform I envision should also have a strong collaborative component to allow feedback and inspiration on flashcard decks. However, I was not prepared for depth of the rabbit hole of spaced repetition research I was about to enter. As it turns out, this is an area where extensive research has been done for more than 100 years, and the number of citations on the seminal paper that more or less started the field of memory research, has been growing exponentially since the early 1980s (Fig. 1. It also turns out that the study findings and recommendations coming out of study technique and memory has largely been ignored. I dove deeply into the research literature because I wanted to know what we know, and what we don't know. On that basis I would then make an honest assessment about spaced repetition and using flashcards. Due to my own failure of making it work, I was prepared for the reality of the evidence perhaps not supporting the efficiency of flashcards. That turned out not to be the case, and I'm still very optimistic about the potential of this project.

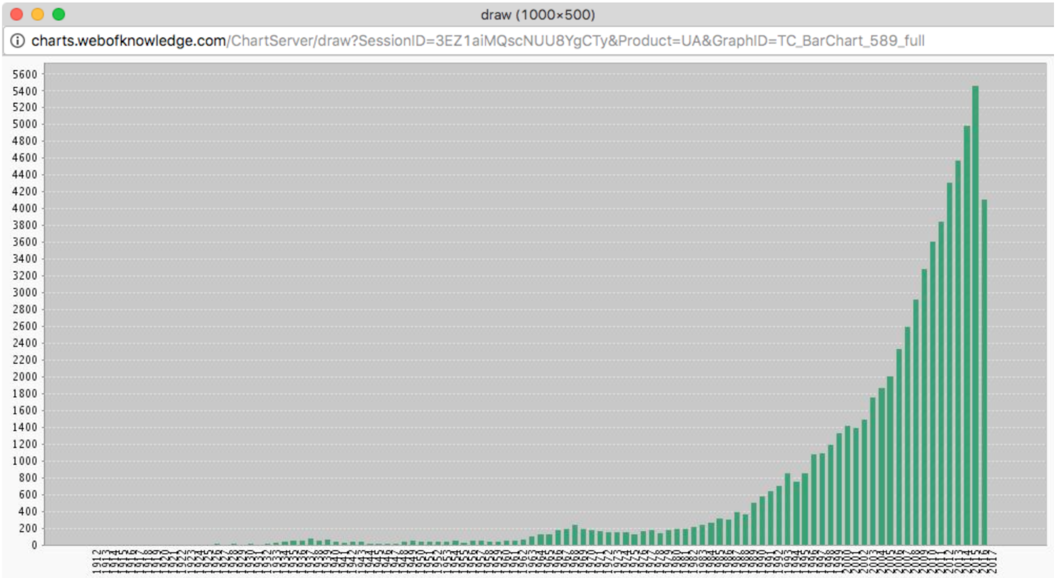

Figure 1: Citations of Hermann Ebbinghaus' 1885 paper years 1912—2016 (Subirana, Bagiati, and Sarma 2017). His work will be introduced in the section on "The Forgetting Curve"

2 Introduction

There are many examples of human traits that makes sense from our the evolutionary path of our species, but that does not serve us so well modern society. One of them may be how we use our memory. As (Subirana, Bagiati, and Sarma 2017) noted:

> From an evolutionary point of view, images and faces may be among the oldest memory retention tasks for survival reasons (to recognize friendly encounters and avoid invading dangerous settings or old enemies).

Our brains were never wired to remember vast amounts of mathematical concepts, physical formulae, dynamics of economy, statistical analyses, languages, and facts of many kinds. But perhaps we can take advantage of what we do know about the memory to optimize retention.

Bryan Caplan is an economics professor at George Mason University and interviewed in a piece for the 2018 January/February issue of The Atlantic[1], said:

> The conventional view—that education pays because students learn—assumes that the typical student acquires, and retains, a lot of knowledge. She doesn't. Teachers often lament summer learning loss: Students know less at the end of summer than they did at the beginning. But summer learning loss is only a special case of the problem of fade-out: Human beings have trouble retaining knowledge they rarely use. Of course, some college graduates use what they've learned and thus hold on to it—engineers and other quantitative types, for example, retain a lot of math. But when we measure what the average college graduate recalls years later, the results are discouraging, to say the least.

It seems plausible that engineers could be in a better position to retain more of their studies than students of the humanities, depending on how rigorously that learned material is applied. But there is still a lot of room for improvement.

The paper "On the Forgetting of College Academics: At 'Ebbinghaus Speed'?" coming out of MIT Office of Digital Learning in June 2017 (Subirana, Bagiati, and Sarma 2017) opened with the abstract:

[1]https://www.theatlantic.com/magazine/archive/2018/01/whats-college-good-for/546590/

> How important are Undergraduate College Academics after graduation? How much do we actually remember after we leave the college classroom, and for how long? Taking a look at major University ranking methodologies one can easily observe they consistently lack any objective measure of what content knowledge and skills students retain from college education in the long term. Is there any rigorous scholarly published evidence on retention of long-term unused academic content knowledge? We have found no such evidence based on a preliminary literature review. Furthermore, findings in all research papers reviewed in this study were consistent with the following assertion: the Ebbinghaus forgetting curve [Ebbinghaus 1880-1885] is a fundamental law of human nature – in fact, of the whole animal kingdom and applies to memory of all types: verbal, visual, abstract, social and autobiographical. This fundamental law of nature, when examined within the context of academic learning retention, manifests itself as an exponential curve halving memory saliency about every two years (what we call "Ebbinghaus Speed"). This paper presents the research group's initial hypothesis and conjectures for college level education programming and curriculum development, suggestions for instructional design enhancing learning durability, as well as future research directions.

I agree with the authors that the lack of long-term studies of skill retention from college education is somewhat mystifying. The little evidence there is seem to suggest an exponential decay (or "Ebbinghaus Curve") with a half-life of two years. They go on:

> Google, the best company to work for according to Fortune, has reported to the New York Times that transcripts "don't predict anything" so they have stopped asking for them, unless you are a few years out of school. As a result Google has been hiring an increasing number of employees without postsecondary education degrees. Google's approach is consistent with the notion that everything is forgotten as our review shows.

The authors also note that despite STEM being ideal for testing the null hypothesis of unused college academics being forgotten at "Ebbinghaus speed", because STEM subjects are:

1. Never used after the final exam
2. Difficult to master
3. Arguably completely unrelated to innate abilities

Unfortunately, the most frequently studied elements by far are those of syllables, series of words, words in a foreign language, personal experiences, number series, emotional memories and the like. "The number of studies that explored memory retention by studying STEM related content appeared to be extremely few and leave many doors unexplored". But there are a few studies, such as one that concluded "About 50% of what is learned in a Mechanics freshman class is lost by the senior year unless it is re-used, in which case performance may even improve.", which is more or less in line with a knowledge half-life of two years.

The learning platform I envision would be generally applicable to any topic and learning situation, however it is designed with the subjects of STEM (Science, Technology, Engineering, and Mathematics) in mind. I think that STEM subjects and (medicine) are some the most challenging to design spaced repetition software for. I will go in depth with the reason for this in the section "Challenges for spaced repetition", but STEM subjects is mainly challenging in flashcards due to the high degree of interrelatedness of concepts.

In this collaborative learning platform, students following the same course or topic of interest could help each other by sharing key insights and take-away points they have learned from lectures or from the reading material, and discuss it with each other. Furthermore, everyone would be saving a collection of these "highlights" of material and be making flashcards[2] for themselves, which they could then revise using spaced repetition.[3] The students should also be able to rate and copy each other's flashcard decks, as well as raise issues and questions about them.

This should support both learning and understanding during the course, and also help to memorize key material well before the exam, thus lightening the study load immediately before the exam. It would also help long-term retention of the material, enabling people to remember much more of what they learned long after the course ends (3 months, 1 year, 5 years etc.). The YouTube video "Simulation of SRS vs. Traditional Review" (Fig. 2) is a visualization of a simple simulation of using spaced repetition vs. other kinds of material review when trying to remember a collection of information.

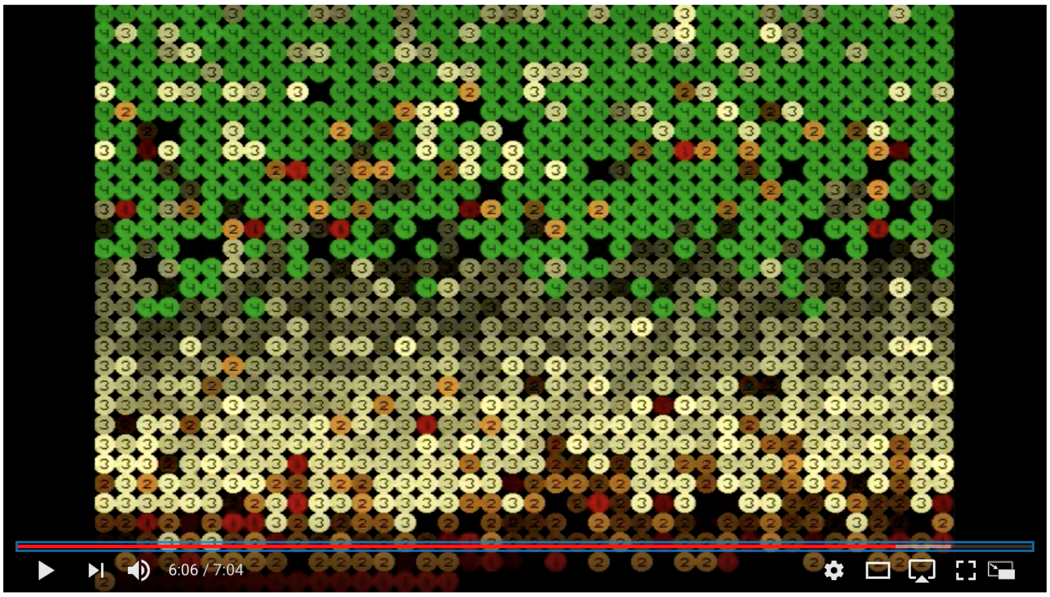

Figure 2: The principle of spaced repetition visualized as memories being energy cells that depletes with time at various rates. The video showcases three different strategies for information review: 1. random, 2. recent and 3. spaced repetition. See video at.[4]

(Kang 2016) notes (emphasis added by me):

> Ample evidence supports the utility of spaced practice in improving educational outcomes. Incorporating spaced practice into education can be a cost-effective approach— **learning becomes more durable in the same amount of time (relative to massed practice), and this can lead to future savings because less time needs to be spent on relearning content that has been forgotten, leaving more time for other productive learning activities** (e.g., higher order analysis, application of knowledge). In short, spaced practice enhances the efficacy and efficiency of learning, and it holds great promise as an educational tool.

[2] A flashcard is a chunk of information with a que or question to trigger active recall of the memory

[3] Spaced repetition is repeated quizzing/retrieval of information, presenting easily recalled information less often and less memorized information more often.

[4] https://www.youtube.com/watch?v=ai2K3qHpC7c

3 Problem Statement

The problem I wish to solve is two-fold:

#1 Much of what a student learns in a course or education is forgotten soon after the exam.

This is fine for the most part. We don't need *all* the things we learn during the course of our life and education. In fact, in a recent article (Richards and Frankland 2017) published in the journal *Neuron*, neurobiologists Blake Richards and Paul Frankland challenge the predominant view of memory, which holds that forgetting is a process of loss (Terada 2017):

> (...) the goal of memory is not just to store information accurately but to "optimize decision-making" in chaotic, quickly changing environments. In this model of cognition, forgetting is an evolutionary strategy, a purposeful process that runs in the background of memory, evaluating and discarding information that doesn't promote the survival of the species.
>
> "From this perspective, forgetting is not necessarily a failure of memory," explain Richards and Frankland in the study. "Rather, it may represent an investment in a more optimal mnemonic strategy."

One could even take the position that important core ideas will come up more often in the course of education and work life, and therefore you will naturally remember these recurrent subjects better than others, and the whole thing works out as a self-optimizing system without the need for a formal memory repetition system. I believe this is only half-true.

When one experience "eureka moments", some of these profound experiences of deep understanding can leave such a lasting impression, that you never really forget them; the feeling of a puzzle piece falling into place in such a way that a big leap in understanding is achieved, e.g. some mathematical structure. Other information is basically "fluff" and will be rightfully buried in memory, as it should be, soon after exposure. However in between these two extremes, there exists a class of insights that are reasonably hard earned (or not) and that are useful to remember, but many times forgotten almost completely. It seems like a waste, because the work required to remember it much better is actually not so substantial due to the shape of the forgetting curve with repeated review intervals (introduced in a later chapter).

It is obviously desirable if a student was able to actively recall the essential parts of her learning and training. One of the benefits would be that many concepts are readily available to be applied without the need to review. An arguably bigger benefit of having essential knowledge well-retained is that ideas can be combined creatively. You can't Google what you don't remember that you know.

#2 During the learning process, students could benefit from each other so much more, with the right tools

During the learning process, all student could benefit from more easily being able to exchange ideas, insights and flashcard material. This could form the basis if their exam preparation, that could then be done gradually instead of being an intensive cramming session at the very end.

In order for me to know what to look for as viable solutions to this two-fold problem statement, I looked to what the scientific research tells us about study techniques.

4 Research Overview on Study Techniques

4.1 What Works

A study of more than 700 scientific articles on 10 commonly used study techniques showed that *self-testing* and *distributed practice* are among the most universally effective study techniques (Dunlosky et al. 2013). They classified study techniques into three categories:

4.1.1 Top strategies

These two study techniques showed consistently good results across age and topics.

1. **Self-testing:** Testing oneself in the material by actively recalling it from memory, as opposed to merely re-reading it and recognizing the information.
2. **Distributed practice:** Spreading out the studying over time as opposed to cramming just before the exam.

From my own observations and from talking to my fellow students, these study techniques are rarely used consistently by students. This is likely due to a lack of awareness of study technique research, but I believe it's also a result of a lack of good tools. In a later chapter I will go more into depth with the software that is already available, and how my proposal is different.

4.1.2 The Runner ups

These three study techniques showed good results in some circumstances and/or still needs more study to determine their usefulness.

3. **Elaborative interrogation:** Asking yourself "Why?", recursively like a children do; "Why does it make sense that. . . ?" or "Why is this true?"
4. **Self-explanation:** Asking yourself "What new information does this sentence provide" and "How does this relate to what I already know?" to make connection with existing knowledge.
5. **Interleaved practice:** Mixing up study sessions to study across the learned material so far instead of linearly trying to master the concepts one after another.

I did found some newer studies with showed convincingly good results for interleaved practice in real-world classroom settings (more on this in the chapter Interleaved Practice).

Another study (Prince 2004) also put emphasis on **peer-to-peer explanations**: "the best available evidence suggests that faculty should structure their courses to promote collaborative and cooperative environments".

4.2 What Doesn't Work

- **Underlining:** was shown to be ineffective "regardless of text length and topic, whether it was aerodynamics, ancient Greek schools or Tanzania" (Dunlosky et al. 2013). It is theorized that it may be that underlining draws attention to individual items rather than connections across items. It is concluded that highlighting and underlining can be useful in the binning of a journey, if the marked information is subsequently turned into flashcards or other forms of self-test (Dunlosky et al. 2013).
- **Re-reading:** The effectiveness of re-reading varied across different types of content, but no benefits were shown beyond the second reading, and self-testing was most often shown to be more effective than re-reading (Dunlosky et al. 2013).

The software proposal in the report will combine the two top methods (self-testing and distributed practice), as well as peer-to-peer explanations and optionally interleaved practice.

5 The Forgetting Curve

Before we can try to solve the first problem in the problem statement, we first need to understand roughly how the memory works.

Robert Bjork[5], the director of the UCLA Learning and Forgetting Lab, a distinguished professor of psychology, and a "massively renowned expert on packing things in your brain in a way that keeps them from leaking out", says in an interview with Wired in 2012 ("Everything You Thought You Knew About Learning Is Wrong" 2012):

> "Forget about forgetting," said Bjork. "People tend to think that learning is building up something in your memory and that forgetting is losing the things you built. But in some respects the opposite is true."
>
> See, once you learn something, you never actually forget it. Do you remember your childhood best friend's phone number? No? Well, Bjork showed that if you were reminded, you would retain it much more quickly and strongly than if you were asked to memorize a fresh seven-digit number. So this old phone number is not forgotten – it lives somewhere in you – but recall can be a bit tricky. And while we count forgetting as the sworn enemy of learning, in some ways that's wrong, too. The two live in a kind of symbiosis in which forgetting actually aids recall.
>
> "Because humans have unlimited storage capacity, having total recall would be a mess," said Bjork. "Imagine you remembered all the phone numbers of all the houses you had ever lived in. When someone asks you your current phone number, you would have to sort it from this long list." Instead, we forget the old phone numbers, or at least bury them far beneath the ease of recall we gift to our current number. What you thought were sworn enemies are more like distant collaborators.

In 1885 the German psychologist Hermann Ebbinghaus tried to memorize a collection of nonsense syllables, and studied how well he could remember these afterwards. He published his seminal work of what would become known as the *forgetting curve*: a curve that shows memory rentention (probablity of recalling some information) vs. time. These results have been replicated many times, one of the latest in a 2015 study (Murre and Dros 2015), see Fig. 3. They found that less than 50% of the syllables were forgotten after 24 hours.

How about "real" course material instead of just nonsense syllables? These typically show significantly longer lifetime, very likely because meaningful information sticks easier to memory easier than nonsense syllables. One study in 2006 that followed students of a consumer behavior course (that included an introduction to statistics), concluded that most of the knowledge gained was effectively lost within 2 years of taking the course (Bacon and Stewart 2006), see Fig. 4.

Another modern example of this loss of knowledge without repetition is a study of cardiopulmonary resuscitation (CPR) skills that demonstrated rapid decay in the year following training. By 3 years post-training only 2.4% were able to perform CPR successfully (Branwen 2009).

The exciting aspect of the forgetting curve is the shape of the curve upon multiple reviews of the information. It turns out that the optimal time intervals between successive reviews is, on average, superlinear.[6] This in turn means progressively longer times between needed review sessions of the particular information.

As an example, after having seen some information for the first time, then in order to maintain a fixed threshold of probability to recall this piece of information, review times could then be scheduled perhaps 24 hours, 1 day, 3 days, 7 days, 30 days, 6 months, 2 years

[5] https://www.psych.ucla.edu/faculty/page/bjork

[6] There has been some debate about uniformly spaced vs. expanding review schedule, but the difference is not substantial, and the expanding schedule is more practical. More will be said on this later.

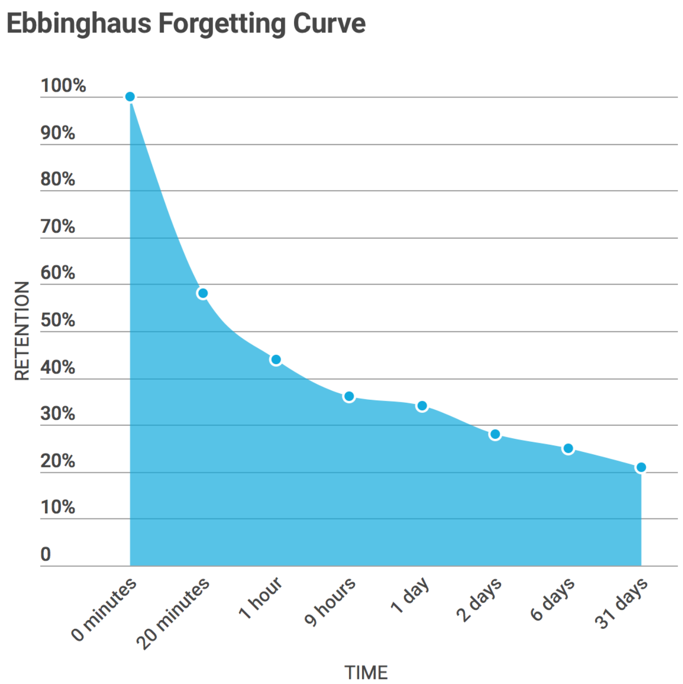

Figure 3: Ebbinghaus forgetting curve replicated in (Murre and Dros 2015)

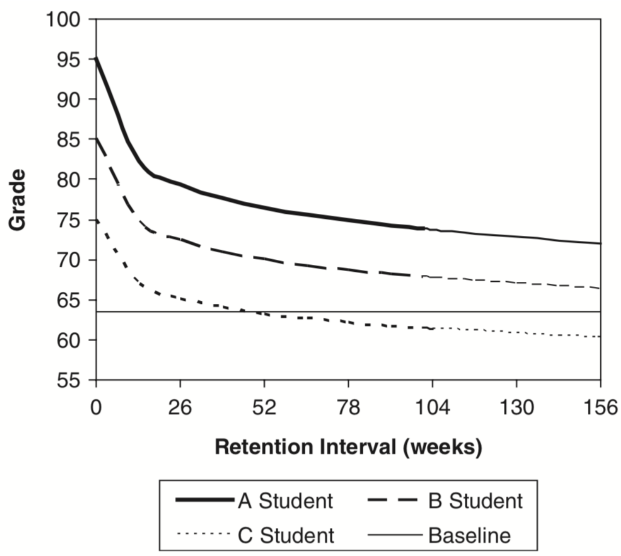

Figure 4: Measured forgetting curve based on multiple choice test of 374 student in a consumer behavior course at a moderate-sized private university in the Western United States, (Bacon and Stewart 2006)

etc., after first encounter with the information, see Fig. 5 (sometimes going a step back if the information is forgotten faster than expected). In other words, it requires progressively less effort to keep things in long-term memory. When done with multiple items, the result is that things that are more easily remembered or seen less often, and things that was harder to remember are seen more often, thus optimizing stidy time. This technique is known as *spaced repetition*.

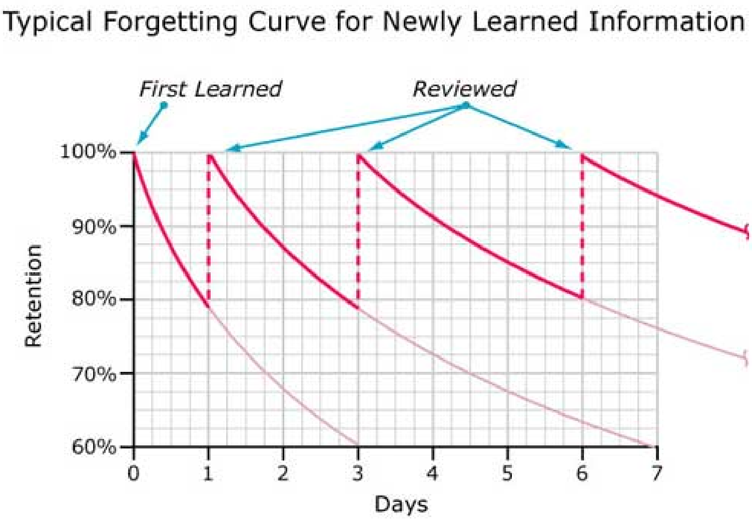

Figure 5: Spaced repetition is based on actively recalling information at the optimal time, e.g. at the time when there is 80% chance of not being able to recall it[7].

A study (Averell and Heathcote 2011) used maximum likelihood (ML) analysis and Markov Chain Monte Carlo (MCMC) to estimate for parameter estimation model selection (between exponential, power and pareto), for a replication of the Ebbinghaus experiment. They found the power function to be the best fit, although the difference between exponential and power did not seem substantial.

We will look at newer models for human memory and scheduling in the section "Optimal Spacing Schedule for Spaced Repetition".

5.0.1 The Leitner System

Scheduling these reviews individually could be a daunting task to do manually. A simplified analog flashcard system was proposed by the German science journalist Sebastian Leitner in the 1970s. There are a number of boxes, for example 5, and all flashcards start in the first box. All flashcards are practiced a number of times, and if answered correctly then "graduates" to the next box, and if answered incorrectly, either put in the previous box or reset to the first box. A study schedule is then set such that boxes with higher numbers are practiced less often than lower numbered boxes.

5.0.2 Notable Spaced Repetition Software

Software that assist in doing spaced repetition is called *spaced repetition software* (SRS) and started to appear in the 1980s. The benefit of having a digital system is that the tedious scheduling can be done by an algorithms, whereas the physical system would be confined to a small number of boxes using the Leitner system. Furthermore algorithms can be adapted

[7]Source: http://www.ellaz.com/AIV/Strategy-3.aspx

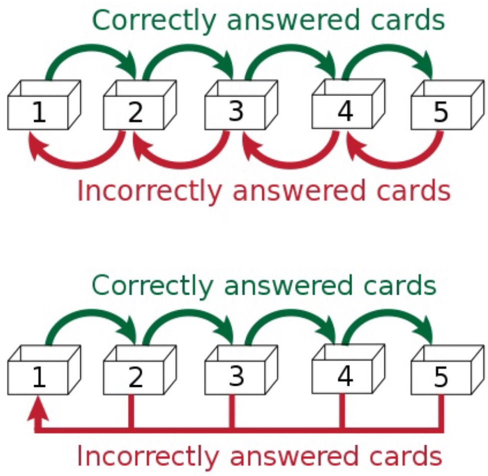

Figure 6: Two versions of the Leitner system for spaced repetition. Top: The Leitner system where correctly answered flashcards are moved to the next, less frequently practiced box, and incorrectly answered flashcards are moved back one box. Bottom: Alternative Leitner system where incorrect answers are moved all the way back to the first box.

and improved. And most importantly digital systems produces a lot of data that can be analyzed and studied for better models of memory and scheduling. SuperMemo developed by the Polish researcher Piotr Wozniak was one of the first if its kind, and featured an algorithm called SM2 (the latest version is SM-17). Wozniak was in many ways a pioneer in the world of SRS[8]. SuperMemo and it's generations of "SM" algorithms form the basis of the algorithms of many other systems. This algorithm takes into account how many times the flashcard has been seen, and the user input of how hard it was to remember, and uses this to set an ideal review date for the flashcard.

Notable examples are of SRS is Duolingo[9], a popular app for learning languages, and Memrise, a similar app that in additional to languages also have decks for more other topics.

Very popular choices for universal SRS applications are Anki an Mnemosyne, both popular because they are free[10] and open source and available on all major platforms (Windows, Mac, Linux, iOS[11] and Android). There are many more options for universal SRS software.[12] Mnemosyne is especially interesting in that it's users can volunteer their data to an open dataset that can then be studied for science. SuperMemo's second iteration of its algorithm from 1987, SM2[13], is notable because it's a very popular algorithm that is being used in many other SRS, including Anki[14] and Mnemosyne[15]. But as we shall see in a later section, more rigorous models than the heuristic SM algorithms have been developed very recently, which no SRS that I'm aware of have implemented yet[16].

[8] For the interested reader, I can highly recommend the piece from Wired back in 2012: https://www.wired.com/2012/01/everything-about-learning/

[9] https://www.quora.com/Does-Luis-Von-Ahn-have-any-plans-for-optimizing-Duolingos-vocabulary-learning-using-spaced-repetition

[10] Anki on iOS is the only application that costs money, to support the person behind Anki, but it's free on all other platforms.

[11] Mnemosyne doesn't have an iOS app.

[12] For a table of flashcard software, see https://en.wikipedia.org/wiki/List_of_flashcard_software

[13] https://www.supermemo.com/help/smalg.htm

[14] Anki uses a slight modification of the SM2 algorithm: https://apps.ankiweb.net/docs/manual.html

[15] https://mnemosyne-proj.org/principles.php

[16] With the possible exception of Knewton where the researcher was an intern as I understand it - but Knewton's product is not purely a SRS

6 Spaced Repetition

Spaced repetition is a very well-documented phenomenon. A study in 2016 found that "Hundreds of studies in cognitive and educational psychology have demonstrated that spacing out repeated encounters with the material over time produces superior long-term learning, compared with repetitions that are massed together", and also that "spaced practice is a feasible and cost-effective way to improve the effectiveness and efficiency of learning, and has tremendous potential to improve educational outcomes" (Kang 2016).

The benefits, it turns out, goes beyond just memory. Spaced practice enhances diverse forms of learning, including (Kang 2016):

- Memory
- Problem solving
- Generalization to new situations
- Augmented learner metacognition

6.1 Why Memorize at All?

(Kang 2016) writes:

> Few would argue that memorizing instructional content, so as to be able to reproduce the information verbatim from memory, is the ultimate goal of education. Nonetheless, acquiring foundational knowledge and being able to quickly access relevant information from memory are often prerequisites for higher order learning and reasoning. For instance, remembering arithmetic facts (e.g., times table) is a critical part of mathematical skill learning, and a transition from calculation to direct memory retrieval of the answer allows more efficient problem solving (e.g., Siegler, 1988)
>
> In short, spaced practice can improve students' memory for essential facts and concepts, which in turn facilitates more complex learning and problem solving.

This fits well into the concepts that Dr. Barbara Oakley and Dr. Terrence Sejnowski have popularized in the Coursera course "Learning How To Learn"[17], and in Oakley's book "A Mind for Numbers: How to Excel at Math and Science";[18] namely:

1. The limited capacity of working memory means that we can give attention to around 3–5 items at the same time.
2. The concept of "chunking" and "chunks" as units of informaton that is understood and stored in memory (short or long term).

Studies have found that the capacity of the working memory naturally differs to a small extend among people[19], and while it can be enhanced a little bit by training, there is a fundamental limit: "We found that by the end of day five... their working memory [capacity] had expanded from one to four items, but not to five."[20]. Since working memory capacity is a fundamental limitation that we can't do much about, we should try and make the best of the working memory that we do have. Oakley describes how chunks of information can be recombined and compounded into higher abstractions, corresponding to higher levels of understanding. For example:

- We practice arithmetic until it becomes second nature, then offload the heavy calculations to a computer.

[17] https://www.coursera.org/learn/learning-how-to-learn
[18] https://www.goodreads.com/book/show/18693655-a-mind-for-numbers
[19] https://www.coursera.org/learn/learning-how-to-learn
[20] http://www.apa.org/monitor/sep05/workout.aspx

- We practice matrix multiplication until it becomes second nature, and then use a computer.
- We practice finding eigenvalues and eigenvectors of matrices until we become fluent in it. Afterwards we are comfortable talking about eigenvalues and eigenvectors when we encounter them in the myriad of applications in science and engineering.

Thus we would never get anywhere if we had to understand everything in terms of the fundamentals everytime we needed to use a concept that is composed of many simpler concepts; we simply wouldn't get anywhere. Oakley herself places enormous weight on fluency[21]:

> Chunks build on chunks, and, she says, the neural network built upon that knowledge grows bigger. "You remember longer bits of music, for example, or more complex phrases in French." Mastering low-level math concepts allows tackling more complex mental acrobatics. "You can easily bring them to mind even while your active focus is grappling with newer, more difficult information."

In conclusion: fluency often comes before understanding. It is not our objective to remember all the details of everything we learn, but to achieve fluency in our craft, and remember the core of the teachings.

6.2 How Effective Is Cramming?

Since cramming is the most popular study technique by students (Kang 2016), it's worth to know just how effective is compared to spaced practice, and how they differ.

And it turns out, cramming works! (Vacha and McBride 1993) That is why students do it. But as (Branwen 2009) noted: "Note that there is no measure of long-term retention, suggesting that people who only care about grades are rationally choosing to cram".

The problem that massed practice leads to *feelings* of fluency, and since it *can* work for increasing the task-performance in the short term, which is all that matters at an exam, students frequently rate massing as more effective than spacing (Branwen 2009):

> Across experiments, *spacing* was more effective than massing for 90% of the participants, yet after the first study session, 72% of the participants believed that *massing* had been more effective than spacing. . . .When they do consider spacing, they often exhibit the illusion that massed study is more effective than spaced study, even when the reverse is true.

Ironically, it was repeatedly shown that low achievers in universities cram the most (Branwen 2009):

> We surveyed 324 undergraduates about their study habits as well as their college grade point average (GPA). Importantly, the survey included questions about self-testing, scheduling one's study, and a checklist of strategies commonly used by students or recommended by cognitive research. Use of self-testing and rereading were both positively associated with GPA. Scheduling of study time was also an important factor: Low performers were more likely to engage in late-night studying than were high performers; massing (vs. spacing) of study was associated with the use of fewer study strategies overall; and all students-but especially low performers-were driven by impending deadlines. Thus, self-testing, rereading, and scheduling of study play important roles in real-world student achievement.

As Nate Kornell, a psychologist at Williams College, put it in an interview with The New York Times, "Forgetting is the friend of learning":

[21] https://www.nytimes.com/2017/08/04/education/edlife/learning-how-to-learn-barbara-oakley.html

> Cognitive scientists do not deny that honest-to-goodness cramming can lead to a better grade on a given exam. But hurriedly jam-packing a brain is akin to speed-packing a cheap suitcase, as most students quickly learn - it holds its new load for a while, then most everything falls out.…When the neural suitcase is packed carefully and gradually, it holds its contents for far, far longer. An hour of study tonight, an hour on the weekend, another session a week from now: such so-called spacing improves later recall, without requiring students to put in more overall study effort or pay more attention, dozens of studies have found.
>
> "The idea is that forgetting is the friend of learning", said Dr. Kornell. "When you forget something, it allows you to relearn, and do so effectively, the next time you see it."
>
> That's one reason cognitive scientists see testing itself - or practice tests and quizzes - as a powerful tool of learning, rather than merely assessment. The process of retrieving an idea is not like pulling a book from a shelf; it seems to fundamentally alter the way the information is subsequently stored, making it far more accessible in the future.

With that out of the way, we will look at the two components of spaced repetition.

6.3 Spaced practice

Spaced practice is studying the same material with some time in between (at least 3–7 days) rather than immediately after (always same or next day). The opposite is called massed practice.

The benefits of *spaced practice* is better retention in the longer-term. Thus the effect may not should up immediately as illustrated in the following study:

> One group of students heard the oath read 6 times in a row; another group heard the oath 3 times on 1 day and 3 more times 3 days later. The students recalled as much as they could immediately after hearing the oath for the sixth time and again 4 weeks later. On the immediate test, the group that received massed repetition recalled slightly more than the group that received spaced repetition. But on the delayed test 4 weeks later, the spaced group clearly outperformed the massed group. While massed practice might appear more effective than spaced practice in the short term, spaced practice produces durable long-term learning

Or as (Branwen 2009) puts it:

> The spacing effect essentially says that if you have a question ("What is the fifth letter in this random sequence you learned?"), and you can only study it, say, 5 times, then your memory of the answer ("e") will be strongest if you spread your 5 tries out over a long period of time - days, weeks, and months. One of the worst things you can do is blow your 5 tries within a day or two.

The spacing effect appears to be so fundamental it can be found in: extends to very different domains and even across species (Branwen 2009):

- Various domains, such as learning perceptual motor skills, learning lists of words etc.
- Across species: Humans, rats, pigeons, flies, bumblebees, seaslugs.
- Across age groups: infancy, childhood, adulthood, the elderly and individuals with various memory impairments.
- Across retention intervals of seconds, days, months, even years.

Read (Branwen 2009) for more details and how spaced practice compares in different domains, in particular how increased lags between practices affects performance.

> Overall, Donovan and Radosevich found that increasingly distributed practice resulted in larger effect sizes for verbal tasks like free recall, foreign language, and verbal discrimination, but these tasks also showed an inverse-U function, such that very long lags produced smaller effect sizes.
>
> In contrast, increased lags produced smaller effect sizes for skill tasks like typing, gymnastics, and music performance.

Concluding (emphasis added by me):

> Skills like gymnastics and music performance raise an important point about the testing effect and spaced repetition: **they are for the maintenance of memories or skills, they do not increase it beyond what was already learned. If one is a gifted amateur when one starts reviewing, one remains a gifted amateur.**

We are here again reminded of the important distinction between learning/understanding and memorizing/practicing.

6.3.1 Why Does Spaced Practice Work?

There are a number of theories:

1. One of the most prominant ones is that repeating an item reminds the learner of it's prior occurance, which triggers retrieval of the past internal representation of the item and it's context. This retrieval process enhances and reinforces the memory by strengthening the old neural pathsways of that memory. Massed repetition eliminates the retrieval process—there is no need to retrieve from memory because the same item was just presented (Kang 2016). This is closely related to the *testing effect*:

   > **The testing effect** is the established psychological observation that the mere act of testing someone's memory will strengthen the memory (regardless of whether there is feedback). Since **spaced repetition** is just testing on particular days, we ought to establish that testing works better than regular review or study, and that it works outside of memorizing random dates in history.

2. Another theory emphasizes the learning context (what surrounds an event, from the external environment to an individual's mental state). With spaced repetitions, the creations of new associations and contexts to the same item may take place, giving multiple "paths" the retrieve the same memory (Kang 2016) and (Branwen 2009).
3. And finally, another theory points to the fact that the attention of a student decrease when it is perceived that the presented information is already known.

The different theories (retrieval of memory enhancing it, new contexts being made with a memory and redudancy reducing attention), are not mutually exclusive, and multiple mechanisms may act in concert to yield the memory advantage produced by spaced practice (Kang 2016).

6.4 Self-testing

Self-testing or *retrieval* is trying to recall information from memory instead of passively re-studying it. The benefits of retrieval was found to boost learning in various ways (Kang 2016):

- Improved memory for the tested information
- Slowed forgetting
- Transfer of learning to new situations

- Generalization to new examples
- Potentiated subsequent learning
- Augmented learner metacognition

A particularly interesting finding is that self-testing does not only improve *memory* but also *generalization*, i.e. the student's ability to apply the knowledge in new situations.

> This review has so far focused on how spaced practice improves memory, in part because memory researchers first observed the spacing effect and also because the majority of prior studies examined memory. **Although acquiring and retaining knowledge matters in education, a more crucial objective is transfer, the ability to utilize what was learned to answer new questions or solve new problems (after all, in real life the likelihood of encountering material in exactly the same way as presented during instruction is exceedingly low)**. Mere remembering of content is rote learning, focused on the past; on the contrary, meaningful learning involves transfer and orients toward the future (Mayer, 2002).
>
> Although the research surrounding the benefits of spaced practice for more complex kinds of learning is not as extensive as that for memory, some evidence indicates that spacing can enhance meaningful learning that generalizes to new situations (see Carpenter, Cepeda, Rohrer, Kang, & Pashler, 2012, for a review). In one study, college students attended a 45-min lecture on meteorology and then reviewed the information (in a quiz with corrective feedback) either 1 or 8 days later (Kapler, Weston, & Wiseheart, 2015). On a final test 35 days after the review session, students in the 8-day condition performed better than those in the 1-day condition not just on the factual recall questions but also on the questions that required application of knowledge. Other studies support spaced practice of mathematics problems (Rohrer & Taylor, 2006) and ecology lessons (Gluckman, Vlach, & Sandhofer, 2014; see also Vlach & Sandhofer, 2012). In addition to improving mathematics problem solving and science concept learning, spaced practice benefits the long-term learning of English grammar in adult English-language learners (Bird, 2010). **In all cases, the students were not just memorizing solutions but were instead applying their learning to solve new problems.**

Regarding the type of self-testing that works best, (Branwen 2009) found by literature review:

> The research favors questions which force the user to use their memory as much as possible; in descending order of preference:
>
> 1. free recall
> 2. short answers
> 3. multiple-choice
> 4. Cloze deletion
> 5. recognition

6.4.1 Downsides to Self-testing

The downsides to self-testing are minor, but worth mentioning (Branwen 2009):

1. **Interference in recall**, where ability to remember tested items drives out ability to remember similar untested items. But "*At worst, interference of this sort might dampen positive testing effects somewhat. However, the positive effects of testing are often so large that in most circumstances they will overwhelm the relatively modest interference effects.*"

2. **Multiple choice tests can accidentally lead to "negative suggestion effects"**, where a previously seen falsehood makes one more likely to believe it. But "This is mitigated or eliminated when there's quick feedback about the right answer".

So we won't worry much about either; the first we won't worry about there is nothing to do about it and reportedly the benefits outweigh the downside, and the second we can make sure to counter by ensuring immediate feedback.

6.5 Spaced Repetition = Testing + Spacing

It was found that the two strategies of retrieval and spacing combined to amplify the benefits of each (Kang 2016). Thus we can say:
Testing + Spacing = Spaced repetition

6.6 Dynamics of Reviewing Similar Memories

(Subirana, Bagiati, and Sarma 2017) brought up a question that is still partially unaddressed in the literature: when is a memory "refreshed" or "practiced", that is, when should we reset the clock to zero?:

> If we review derivatives, are we also implicitly reviewing integrals? If we review how the Pythagoras theorem can be derived, are we also reviewing how it can be applied?

This question I do think we should be able to answer through data analysis of a suitably designed SRS such as the one proposed in this report. The little evidence there is seem to suggest both that reviewing concept do *somewhat* transfer to related concepts, and also that other factors such as practical application of knowledge and emotional impact may be important (Subirana, Bagiati, and Sarma 2017):

> Direnga et al [42] showed that members active in the subject show improvements which may mean that Ebbinghaus speed does not applied if "similar" concepts are reviewed. Fritz et al [43] tested retention over a 6-month period and found using a simple model to explain a concept is equal to a sophisticated model in terms of retention of medical instruction suggesting other factors, such as emotional impact, are essential to retention.

6.7 When to Use Spaced Repetition

Based on empirical findings by Piotr Wozniak[22] and some back of the envelope calculations, Gwern arrived at rule-of-thumb (Branwen 2009):

> 5 minutes is the line that divides trivia from useful data. (There might seem to be thousands of flashcards that meet the 5 minute rule. That's fine. Spaced repetition can accommodate dozens of thousands of cards).

What if one is in a hurry for an exam? (Branwen 2009) estimates:

> To a lesser extent, one might wonder when one is in a hurry, should one learn something with spaced repetition and with massed? How far away should the tests or deadlines be before abandoning spaced repetition? It's hard to compare since one would need a specific regimens to compare for the crossover point, but for massed repetition, the average time after memorization at which one has a 50% chance of remembering the memorized item seems to be 3-5 days. Since

[22] https://www.supermemo.com/articles/programming.htm

there would be 2 or 3 repetitions in that period, presumably one would do better than 50% in recalling an item. 5 minutes and 5 days seems like a memorable enough rule of thumb:

"Don't use spaced repetition if you need it sooner than 5 days *or* it's worth less than 5 minutes".

I will note that these results are only strictly applicable to standalone-facts, where it's all about the space-time tradeoff[23], but does not necessarily apply to highly interrelated information that is "chunked" to achieve higher abstraction levels.

[23]https://en.wikipedia.org/wiki/Space–time_tradeoff

7 Challenges and Tips for Spaced Repetition

By broad survey I have found the most common complaints and mistakes with spaced repetition to be:

- **Formulating poor questions and answers** (Branwen 2009)
- **Memorizing before learning:** Assuming it will help you learn, as opposed to maintain and preserve what one already learned. It's hard to learn *from* cards, but if you have learned something, it's much easier to then devise a set of flashcards that will test your weak points. (Branwen 2009)
- **Loss of context:** Flashcards are less useful to learning the "big picture". If you are memorizing a large amount of information, there is often a hierarchy, organization, etc that can make leaning the whole thing easier, and you loose the constant visual reminder of the larger context when using flashcards.[24]
- **Flashcards not taking advantage of spatial, mapping, or visual memory**, all of which the human mind is much better optimized for. It is not so well built to memorize pairs between seemingly arbitrary concepts with few to no intuitive links. My preferred methods are, in essence, hacks that use your visual and spatial memory rather than rote.[25]
- **Overload:** Feelings of overwhelm as the daily flashcard review number becomes too big.

Some of the problems there are definite remedies against, and some there is still somewhat lack of in-depth studies. We will now address the problems listed above.

7.1 General Tips for Flashcard Creation

Piotr Wozniak, the Polish scientist behind SuperMemo, is the author is a webpage "Effective learning: Twenty rules of formulating knowledge"[26] that in my experience is one of the most cited lists of good flashcard creation practices.

Here is my interpretation of the most important ones:

- **Learn before you memorize** - you need to build an overall picture of the learned knowledge. *Remember: it's spaced repetition, not spaced learning.*
- **Make cards minimal** - break down the information to the simplest chunks that still makes sense, instead of filling the card with multiple facts.
- **Use imagery** - to involve our visual cortex, which is strongly associated with memory.
- **Use mnemonic techniques** - take advantage of the brain's natural power to remember quirky things and stories - the more crazy and memorable the better.
- **Rely on emotional states** - Use objects that evoke very specific and strong emotions: love, sex, war, your late relative, object of your infatuation - it is well known that emotional states can facilitate recall.
- **Refer to other memories** - Can place your item in a better context, simplify wording, and reduce interference.

This list can be extended with what I believe are good heuristics around making flashcard, form own experience and reading other people's experience:

[24] A user on LessWrong.com used Flashcards extensively for 3 years in medical school, and after failing to receive any substantial benefits and meeting with a learning-skills specialist, wrote an article about it: http://lesswrong.com/lw/juq/a_vote_against_spaced_repetition/

[25] A user on LessWrong.com used Flashcards extensively for 3 years in medical school, and after failing to receive any substantial benefits and meeting with a learning-skills specialist, wrote an article about it: http://lesswrong.com/lw/juq/a_vote_against_spaced_repetition/

[26] https://www.supermemo.com/en/articles/20rules

- **Make your own flashcards**
- **Only include the most important** - Use 80/20 rule to narrow down the best stuff.
- **Don't make flashcards immediately** - Be careful to make flashcards on the run, while learning the material. It is often more effective first apply the concept a few times first, rather than having to rewrite almost every flashcard.
- **Why questions** - Cards that answer the question "Why?" are more valuable than factual cards.
- **Say your answers loud when studying** - has been confirmed by recent study to work (Forrin and MacLeod 2017)
- **Study your flashcards in both directions** - meaning that both sides of the card can act like question and answer.
- **Don't treat flashcard like a silver bullet** - Write an explanation in your own words, create a quiz, take a practice test written by someone else, work lots of practice problems (your go-to strategy for math), make mind maps or Venn diagrams etc.[27]
- **Don't practice mindlessly** - Actively trying to retrieve memories is more important than finishing quickly.
- **Don't study in one big session** - Use you small windows of time, e.g. the bus stop, time between classes etc.

For good lists of tips see.[28][29][30]

7.2 The Question of Context

Is there a loss of context, or *hindering of abstraction* with the use of flashcard? This is one of the most important and legitimate questions about flashcards in my opinion. The usage of spaced repetition is straight forward when it comes to simple facts. In fact, "Robert Craig set multiple records on the quiz show *Jeopardy!* 2010-2011 in part thanks to using Anki to memorize chunks of a collection of >200,000 past questions; a later Jeopardy winner, Arthur Chu, also used spaced repetition" (Branwen 2009).

However things are not so simple with concept on a higher level than simple facts (Branwen 2009):

> [A] potential objection is to argue that spaced repetition inherently hinders any kind of abstract learning and thought because related materials are not being shown together - allowing for comparison and inference - but days or months apart. Ernst A. Rothkopf: "Spacing is the friend of recall, but the enemy of induction" (Kornell & Bjork 2008, p. 585). This is plausible based on some of the early studies but the 4 recent studies I know directly examining the issue both found spaced repetition helped abstraction as well as general recall:

Like Gwern, I also found most newer papers optimistic, such as (Subirana, Bagiati, and Sarma 2017), but I also have my own take on this.

I think this is a really important subject, if one wish to apply spaced repetition to fields such as science and engineering. I have personally experienced limits to the effectiveness of the SRS system Anki during my own experiements with it, and it needs to be addressed.

My answers is that here needs to be:

1. **A concept of closely related flashcards that logically makes sense to group together when reviewing flashcards on that particular subject.** The user should have granular control over the size of these clusters. Logically there should be an optimum; too small clusters (down to single cards), and the flashcard review can

[27] https://collegeinfogeek.com/flash-card-study-tips/
[28] http://rs.io/anki-tips/
[29] https://collegeinfogeek.com/flash-card-study-tips/
[30] http://skillcookbook.com/flashcards/

feel too unfocused and not enough emphasis is put on the links between flashcards. Too big clusters, and the benefits of interleaving is likely to be lost, and there is a risk of the student receiving too many hints to various flashcards instead of retrieving from memory. I have not been able to find any rigorous studies on the effectiveness on various sizes of these relatedness-clusters, and it's clear that more studies are needed. Such as study would be helped immensely by the data that would be generated from the proposed learning platform that is the subject of this report.

2. **A concept of dependency, i.e. a mechanism to present certain cards before others could be tested**. It's not a given that a particular order / dependency is needed of there is a concept of a related set of cards, but it's an option that should be studied.

As reviewed earlier, our minds use chunks and clusters. You want as many connections to each fact.

One thing must be noted in about tip on making cards minimal; not all subjects are "coercive to flashcards" or some would say "flashcard-eligible". As user noted[31]:

> **Not all subjects are flashcard-eligible**. You need to be aware of that. Memorizing chapters of a book by making flashcards is one of the least effective ways of remembering the content of those chapters as a whole. Trying to recall the content while giving little explanations as if you're giving a lecture is a far more effective way to do it. And I always get something different every time I read the same book. Anki only tells me when I'm about to forget that, and if I wanted to retain that knowledge, I'd better review it decently.
>
> **Your cards must act as indexes.** Your brain should be an index. Every time that I begin to make too much mistakes on certain flashcards, it's CLEAR that you're not remembering because you DIDN'T learn it correctly in the first place, not because anything else. So you mark that card, go back and review your book, lecture, notes, resource and make a couple more flashcards of that tiny bit that you're getting wrong every time.

Another user also resisted the idea of flashcard necessarily being completely broken down, atomized pieces of information[32]:

> **Use a card to remind you to think**
>
> For decks with higher level concepts like Algorithms or Game theory every time I review a card I explain it and I let me my mind linger and come up with associations. It's rare the card where at least 1 or 2 associations new associations don't pop in my mind including questions. Besides that it's also usually the case that when I try to explain a concept I find little nuances or questions that I then research. And that builds new associations too.
>
> This requires time, of course, that's why I find it important to prune knowledge aggressively. I am generally eager to add new knowledge and overestimate its value.

So instead of treating flashcards merely as a "game" of getting a high retrieval score. "Instead, whether I happen to have perfect recall or not, I should focus on: 'This is my time to *think about this again*.'[33]Many users in STEM fields, have found flashcards to be useful simply for triggering a whole network of association around a concept, due to the nature of the highly interconnected concepts in STEM:

[31]reviewing-thinking
[32]https://yourawesomememory.com/content/reviewing-thinking
[33]https://yourawesomememory.com/content/reviewing-thinking

> **I'm a Human, Not a Computer** Computers can't think. But they can copy terabytes of data in a few minutes. If I view Anki as copying data into my brain, it will drive me nuts that it takes so many hours to copy so few bits of data. It makes me feel like a shoddy, vacuum-tube prototype mainframe that keeps chewing up its punchcards. But if I view Anki as triggering thoughts, awakening whole networks of experiences and associations, then remembering will make me more human. I won't review for the sake of awesome, high-quality thinking later. My reviews will be that high-quality thinking. Right now.

The people behind SuperMemo regularly responds to critique in their wiki. In response to the particular critique about not being able to maintain "the big picture" in an SRS system, they responded[34]:

> The argument that SuperMemo does not hold the "big picture" is as old as SuperMemo. The answer is always the same: you do not need the big picture in SuperMemo as long as you keep it in your head. Many students fail this principles and their effectiveness in using spaced repetition is also undermined.
>
> Students may give up spaced repetition at their own peril. Without review, memories disappear. Spaced repetition helps minimize the review. However, the entire process relies heavily on smart learning, right choices, material selection, item formulation, and other learning strategies.
>
> Smart learning is difficult because it requires that you be ... well ... smart.

7.3 Overload

Many users of SRS report being overwhelmed by the system. It could be that they add a lot of trivial things they don't care about, or that they add relevant stuff but too fast.

This point will be addressed in the section "Paper Summary on Optimizing Spacing Schedule" where model for optimal inflow rate of new cards is developed.

[34] http://supermemopedia.com/wiki/A_vote_against_spaced_repetition

8 Interleaved Practice

We briefly touched upon *interleaved practice* in section "What Works" i.e. learning `AAABBBCCC` `vs ABCABCABC`.

Studies of interleaved practice shows most improvement of learning in mathematical knowledge (Kang 2016). It makes sense that subjects in science and engineering is where interleaved practice really shines because forces the student into thinking about a broader range of learned concepts and which one to apply (and why), instead of knowing that this problem must belong to a certain chapter. Therefore interleaved practice makes the learning situation more similar to an actual exam or even real-life application.

Interleaving has also shown to benefit in fields of category discrimination such as recognition and classification of art (Kang 2016). "Students after blocked practice had difficulty discriminating among the problem types and knowing when to use which formula. Therefore, similar to category learning, interleaved practice seems to help learners differentiate among the types of problems they are learning to solve" (Kang 2016).

It has also been suggested that attentional lapses can play a role. A study found that mind wandering is more likely during blocked than interleaved training (Kang 2016). When presented with material that is completely different, the mind is less likely to wonder.

In conclusion, "**multiple mechanisms may underlie the interleaving advantage: Attention, temporal spacing, and juxtaposing different categories could jointly contribute to learning**." (Kang 2016)

Where does interleaved practice fit into a SRS flashcard system? Quite simply, reviewing flashcards is inherently interleaved, to the degree one chooses not to group related cards together for review (see discussion in section The Question of Context).

Finally I will briefly mention that some very promising studies have been done on using interleaved in the classroom simply by reorganizing the homework assignments, which could be sufficient to produce sizable gains! This is research I wish DTU would recognize and start to implement on an experimental basis. I quote and emphasize the relevant section in Appendix A.3.

9 Optimal Spacing Schedule for Spaced Repetition

Robert Bjork[35] in his 2012 Wired interview ("Everything You Thought You Knew About Learning Is Wrong" 2012):

> The spacing effect was one of the proudest lab-derived discoveries, and it was interesting precisely because it was not obvious, even to professional teachers. The same year that Neisser revolted, Robert Bjork, working with Thomas Landauer of Bell Labs, published the results of two experiments involving nearly 700 undergraduate students. Landauer and Bjork were looking for the optimal moment to rehearse something so that it would later be remembered. Their results were impressive: The best time to study something is at the moment you are about to forget it. And yet — as Neisser might have predicted — that insight was useless in the real world. Determining the precise moment of forgetting is essentially impossible in day-to-day life.

While it is an impossible task to determine this moment precisely for everything we wish to remember, some progress has been made recently.

9.1 Single Review Opportunity

Let's start with the simplest situation: Given that you know the test date, and you have a single review opportunity, when should you use it? Of course, reviewing the test the same day, or day before the final test would probably always give the best results on the test. But given what we have established about the benefits of spaced practice, it is more interesting to look at this question while subject the constraint that there is always being a gap between review session and test session of at least 7 days, which is what the following study did.

A large experiment examined 10 different lags (the spacing between initial learning and retrieval practice review, that ranged from 0 to 105 days) and four different retention intervals. The final test was administered either 7, 35, 70, or 350 days *after* the review session. **They found that retention was highest "when the lag was about 10% to 20% of the tested retention interval.** In other words, there is no fixed optimal lag—It depends on the targeted retention interval. If you want to maximize performance on a test about 1 week away, then a lag of about 1 day would be optimal; but if you want to retain information for 1 year, then a lag of about 2 months would be ideal."(Kang 2016). This comes with the ceveat that this was study material was trivia facts, but it gives a sense of a ballpark figure.

9.2 Multiple Review Opportunity

When you have multiple review opportunities, the natural question becomes: what if you want to optimize a review schedule for *mastering* the maximum amount of information for the long term, given some time constraints, rather than just optimize for a test on a specific date?

As we have established, spacing out the multiple review opportunities produces better learning than massing them together. There has been some debate as to whether the multiple reviews should be spaced out uniformly, or in an expanding schedule (meaning the lag progressively increasing between each review). Most of the sources I have found suggest an expanding schedule to be most effective, including (Kang 2016) and (Branwen 2009).

We shall look at a recent paper where an effort was made to put multiple review spacing schedule in a more rigorous mathematical framework, use data analysis as a means of memory model selection, and Amazon Mechanical Turk to verify the findings.

[35] https://www.psych.ucla.edu/faculty/page/bjork

9.3 Paper Summary on Optimizing Spacing Schedule

This section will go summarize the findings in the paper "Unbounded Human Learning: Optimal Scheduling for Spaced Repetition" (Reddy et al. 2016) due to it's importance, and for including some of the latest technical work in this area. It is the most technical section in this report and the best attempt at a rigorous mathematical model I have seen so far, with the ultimate goal of deciding the optimal frequency with which new cards should be introduced into a flashcard deck to order to optimize the "throughput" of flashcards, i.e. number of mastered flashcards per unit time, within some constraints of study time. I recommend reading the full paper for anyone interested in the mathematical modeling of memory and spaced repetition.

They make three contributions:

1. **Mining large-scale log data to validate human memory models:** They perform observational studies on a user data from the Mnemosyne SRS application, with a dataset containing 859,591 interactions, 2,742 users, and 88,892 items.
2. **Mathematical modeling of optimal spacing schedule**, by embedding above memory model into a stochastic model using *queue theory*, and verifying by running simulations. As an aside, the main author have also modeled this using a neural network to do *reinforcement learning* in another more recent paper (Reddy, Levine, and Dragan, n.d.). I will not to into detail with the reinforcement learning approach here since I have not had time to study it in-depth yet.
3. **Verification of the mathematical model in controlled experiments**, by hiring people on Amazon's Mechanical Turk.

9.3.1 Paper Introduction

> Existing schemes for assigning review frequencies to different decks are based on heuristics that are not founded on any formal reasoning, and hence, have no optimality guarantees. One of our main contributions is a principled method for determining appropriate deck review frequencies.
>
> The problem of deciding how frequently to review different decks in the Leitner system is a specific instance of the more general problem of review scheduling for spaced repetition software. The main challenge in all settings is that schedules must balance competing priorities of introducing new items and reviewing old items in order to maximize the rate of learning. While most existing systems use heuristics to make this trade-off, our work presents a principled understanding of the tension between novelty and reinforcement.

9.3.2 1: Testing Human Memory Models

This section seeks to fit variations of a standard exponential forgetting curve model, where recall is binary (user is assumed to either completely recall or forget an item), and the probability of recalling an item has the following function form:

$$P(\text{recall}) = \exp\left(-\theta \cdot d/s\right).$$

They use a 0-Parameter and 1-Parameter Logistic Item Response Theory models (0PL-IRT, 1PL-IRT) + a logistic regression model as benchmark models, and compare 10 different exponential decay models containing various combinations of the variables:

- d_{ij} as the time elapsed since previous review of item i by user j.
- q_{ij} for position (i.e. deck number) of item i in Leitner system for user j.
- n_{ij} as the number of past reviews of item i by user j.
- θ as a global item difficulty, i.e. assuming that all items are equally difficult to memorize.

- θ as a item-specific difficulty, i.e. we assume that some items may be easier to forget than others.

All other models are trained using maximum-likelihood estimation, and they follow all the usual practice of cross validation.

Observations:

1. **Positive impact of delay terms:** Models with delay term d_{ij} (time elapsed since last review) perform better than models without it.
2. **Use of item-specific difficulties:** Item-specific difficulties θ_i outperforms global difficulty θ. However, they end up using global difficulty "due to considerations of practicality (θ_i may be unknown and/or difficult to estimate) and mathematical tractability"
3. **Leitner position >> number of reviews >> constant memory strength:** Setting memory strength s equal to Leitner deck position q_{ij} performs better than it proportional to the number of past reviews n_{ij}, which in turn is better than using a constant s.
4. **Performance comparable to best logistic regression model** Setting memory strength s equal to Leitner deck position q_{ij} performs better than it proportional to the number of past reviews n_ij, which in turn is better than using a constant s.

9.3.3 2: A Stochastic Model for Spaced Repetition Scheduling

Where the second section of the paper sought to find a suitable model of human memory, the third section seeks to find an optimal scheduling strategy for flashcards in the Leitner system, based on the memory model from the previous section. A Leitner system was modelled using queuing theory, see Fig. 7. **In this model, a card is considered to be mastered when it is successfully recalled at the last card deck** n (in Fig. 7 that is deck 5).

And most crucially, it's assumed that the learner has a review frequency budget (e.g., the maximum rate at which the user can review items) of U, which is to be divided between reviewing the decks as well as viewing new items.

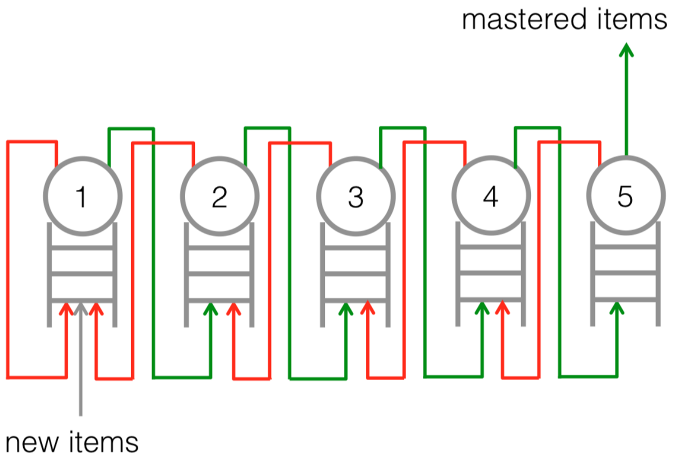

Figure 7: The Leitner Queue Network: Each queue represents a deck in the Leitner system. New items enter the network at deck 1. Green arrows indicate transitions that occur when an item is correctly recalled during review, and red arrows indicate transitions for incorrectly recalled items. Queue k is served (i.e. chosen for review) at a rate μ_k, and selects items for review in a FIFO manner.[36]

[36]Figure text taken from paper (Reddy et al. 2016)

The learning rate λ_{out} is defined to be the long-term rate of mastered items exiting from deck n, i.e.:

$$\lambda_{out} = \lim_{T\to\infty} \frac{1}{T} \cdot |\{\text{Items mastered in interval } [0,T]\}|$$

The aim of a scheduling policy is to maximize λ_{out}.

It is assumed that new items are injected into deck 1 following a Poisson process with a chosen rate λ_{ext} ("arrival rate"), and for each deck k, we choose a "service rate" μ_k, which represents the rate at which items from that deck come up for review. We need to enforce that the arrival rate λ_{ext} and deck service rates together satisfy the user's review frequency budget constraint, i.e., $\lambda_{ext} + \sum_k \mu_k \leq U$. The problem is then to choose the decision variables, arriaval rate λ_{ext} and service rates μ_k, such that the learning rate λ_{out} is maximized.

I won't go into details here, but in summary the strategy was the following: a vector state was defined for each deck, forming a Markov chain and finally using a so-called "mean-recall approximation" to reduce the problem to a low-dimensional deterministic optimization problem.

The primary qualitative finding to come out of this paper is a partiular property of the optimal review schedule of a Leitner Queue Network (LQN): the existance of a phase transition in the form of a threshold arrival rate λ_t, at the optimum arrival rate, see Fig. 8. Given some set of service rates μ_k, there would a threshold arrival rate λ_t such that for all $\lambda_{ext} > \lambda_t$, cards could start to accmulate on the first deck without limit. This is interesting because one of the most common complaints about SRS is the user experiencing overwhelm in form of a huge number of card reviews, which can set the user on a slippery slope towards an insurmountable daily review count, which often leads to abandonment of the software, or even disillusionment of the whole concept of spaced repetition software.

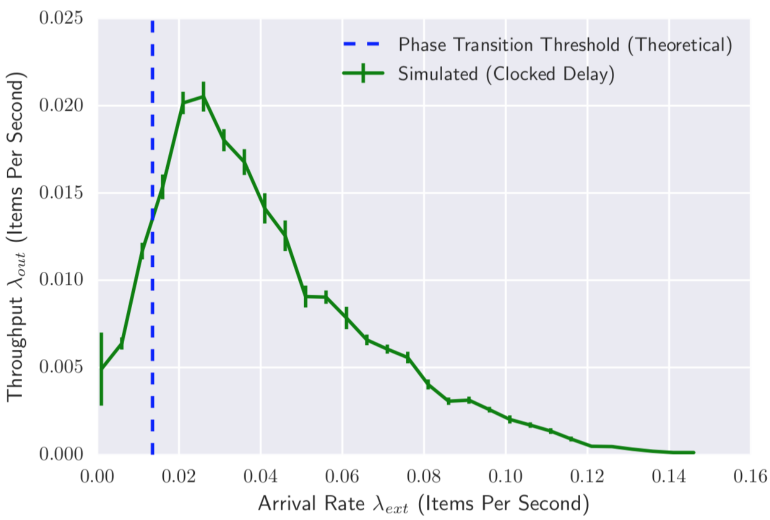

Figure 8: Phase transition in learning: Average learning rate λ_{out} vs. arrival rate λ_{ext} in the Leitner Queue Network with clocked delays, for a session of 500 reviews over 50 items. We set number of decks $n = 5$, review frequency budget $U = 0.1902$, and global item difficulty $\theta = 0.0077$. The dashed vertical line is the predicted phase transition threshold under the mean-recall approximation.[37]

Other minor findings:

- Slightly convex graph of "Learning rate λ_{ext} vs. U", for low values of U, meaning increasing returns, at least for low values of U. That is, if you decide to study a little

[37]Figure text taken from paper (Reddy et al. 2016)

more, the increase in optimal learning rate λ_{ext} is at least proportional to this study budget, or better than linear, which is an encouraging for using the system.

- Simulations of the LQN also provided support for the empirical observations in the literature for expanding intervals between repetitions.
- Exploration through simulation of optimal study strategies, assuming non-uniform item difficulty, it was found that easy items should spend roughly the same time in each deck, whereas more difficult items should spend more time in the lower decks than higher decks.

9.3.4 3: Experimental Validation

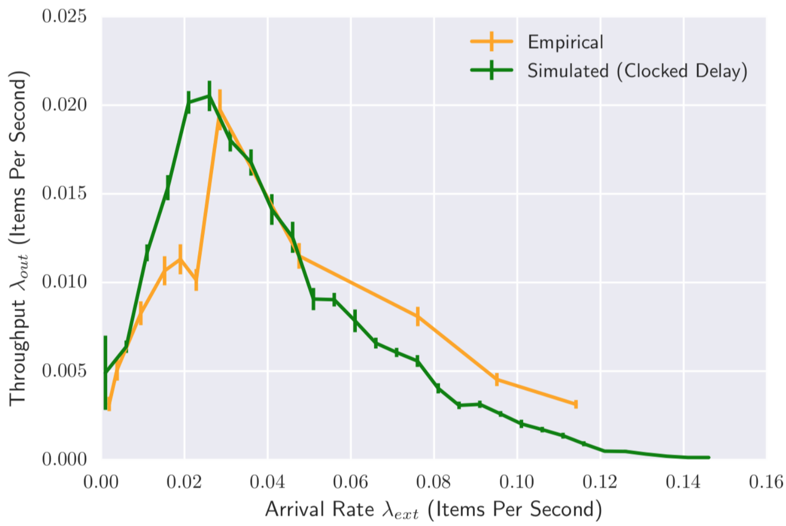

Figure 9: The exit rate λ_{out} vs. arrival rate λext, where number of decks $n = 5$, review frequency budget $U = 0.1902$, and global item difficulty $\theta = 0.0077$.[38]

We see that the phase transition that was found in theoretic analysis and simulations in the previous sections are found again the in experimental validation in Fig. 9.

> As the arrival rate increases past the optimum, relatively fewer items are mastered and relatively more items get 'stuck' in deck 1. Intuitively, the user gets overwhelmed by incoming items so that fewer and fewer items get reviewed often enough to achieve mastery. Fig. 10 and Fig. 11 match the behavior suggested by our queueing model: for injection rates higher than the threshold, the number of items in deck 1 blows up while the other decks remain stable.

9.3.5 Paper Conclusion and Open Questions

> Our work develops the first formal mathematical model for reasoning about spaced repetition systems that is validated by empirical data and provides a principled, computationally tractable algorithm for flashcard review scheduling. Our formalization of the Leitner system suggests the maximum speed of learning as a natural design metric for spaced repetition software; using techniques from queueing theory, we derive a tractable program for calibrating the Leitner system to optimize the speed of learning. Our queueing framework opens doors to

[38]Figure text taken from paper (Reddy et al. 2016)
[39]Figure text taken from paper (Reddy et al. 2016)
[40]Figure text taken from paper (Reddy et al. 2016)

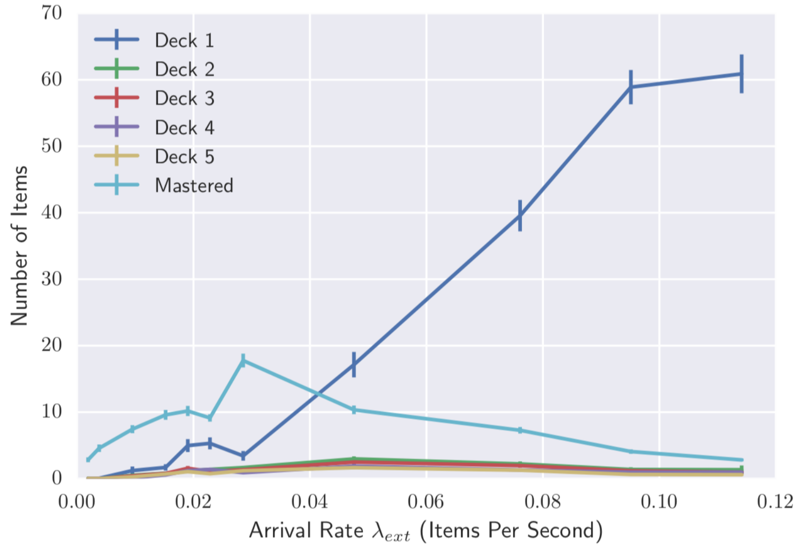

Figure 10: The number of items that finish in each deck vs. arrival rate λ_{ext}, where number of decks $n = 5$, review frequency budget $U = 0.1902$, and global item difficulty $\theta = 0.0077$.[39]

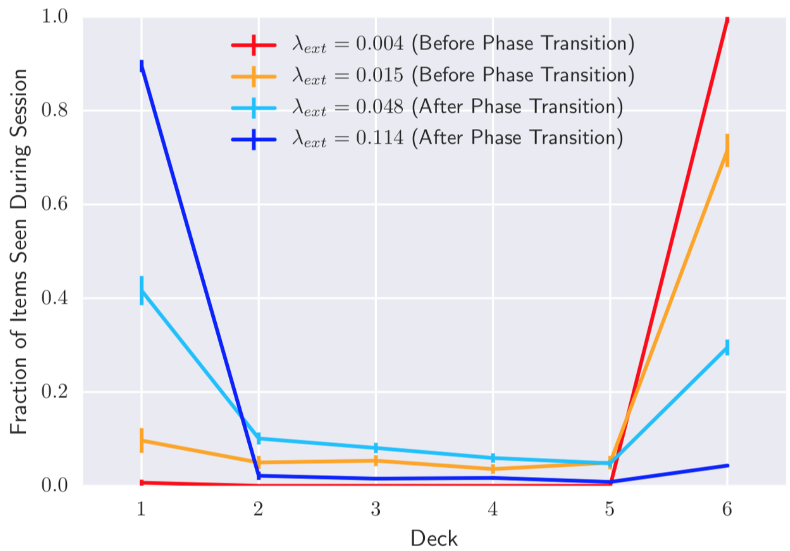

Figure 11: The fraction of items seen during a session that finish in each deck for different arrival rates λ_{ext}, where number of decks $n = 5$, review frequency budget $U = 0.1902$, and global item difficulty $\theta = 0.0077$. Deck 6 refers to the pile of mastered items.[40]

leveraging an extensive body of work in this area to develop more sophisticated extensions. To inspire and facilitate future work in this direction, we release (1) all model and evaluation code, (2) framework code for carrying out user studies, and (3) the data collected in our Mechanical Turk study. The data and code for replicating our experiments are available online at http://siddharth.io/leitnerq.

Our work suggests several directions for further research. The primary follow-up is to obtain a better understanding of the Leitner Queue Network; in particular, better approximations with rigorous performance guarantees. Doing so will allow us to design better control policies, which ideally could maximize the learning rate in the transient regime. The latter is critical for designing policies for cramming, a complementary problem to long-term learning where the number of items to be learnt is of the same order as the number of reviews. Next, our queueing model should be modified to incorporate more sophisticated memory models that more accurately predict the effect of a particular review schedule on retention. Finally, there is a need for more extensive experimentation to understand how closely these models of spaced repetition apply to real-world settings.

10 Solution Discussion

10.1 The Case for Taking Notes

When the student experiences a moment of understanding in a learning process (let's call it an "insight"), there are several good reasons to write it down:

- The student may simply forget it, so it is worth noting down for review later.
- The simple act of writing it down makes it more likely to be remembered. Especially in handwriting (May 2014), at least as a first iteration, in which case it can be written in computer text later.
- Even if the student have a very good memory, or has been experiencing to be doing fine without any note-taking whatsoever, the student may have an especially good way of explaining it, which could benefit other students in various situations:
  - A student that is struggling to understand the same concept could benefit from an alternative explanation than that presented in the book or lecture.
  - A student who *think* they understand it, but have misunderstood a concept partially or completely.
  - A student who also understand it, but in a different way could benefit of an alternative explanation, interpretation or mnemonic.
  - Finally, the note could quickly be converted into a flashcard for easy quizzing for the exam, and long-term retention after the course has ended, if desirable.

The good students are most often very willing to help, and by engaging with the rest of the course, students can act as each other's TAs. It is also often the case that both the student providing and receiving help benefits from this interacting.

10.2 Review Old Class Notes, Books and Video Lectures... Really?

The study involving the MIT Office of Digital Learning suggests making a habit out of reviewing (Subirana, Bagiati, and Sarma 2017) (emphasis added by me):

> Most notably the key practical advice from our research is that one should just accept the truth: forgetting is unavoidable. Humans in the jungle seem to have evolved to best memorize one year or two (so that only repeated things get memorized), and with time, say 10 years, mastery reaches its peak. The stronger you memorize something, the higher you start on the forgetting curve and the longer you have before reviewing is your only retention option. **If interested in learning for life, one should budget time for re-training before forgetting occurs (and not sooner), even a mild contact with memory makes it extend its useful life. Make it a habit to review your class notes, books or even video lectures.**

If anyone can bring themselves to spend time on reviewing old class notes, books and video lectures, that is admirable. I believe there is a better way, which is to produce condensed notes and flashcards (as one unified material) during learning in collaboration with peers, and then use *that* to review old classes and courses, falling back on the original material only if one really want to go in-depth (using deep linking from notes as suggested).

And finally (Subirana, Bagiati, and Sarma 2017) concludes:

> First mastery, then retention strategy is what most affects the degree of learning (many heuristics have been suggested). Plan to use the skills you know in the following two years (and if not, intensively re-train). Unless you objectively test your memory, your perception of accuracy will certainly be wrong and it

may be too late when you find out. Your capacity to memorize does not age, your memories do. **Your first job may be the most impactful decision in terms of how valuable your time at school was (BA, M.Sc, PhD). If related to your field of study you may be able to use the knowledge and vastly improve the forgetting threshold. If not, in two years you may lose everything you got out of it.**

This exactly part of the problem I wish to solve.

10.3 Solution Discussion for the Context Problem

We will now revisit the problem of using SRS for conceptual subjects, but with suggestions for solutions this time.

Spaced repetition is straightforward for very fact-based subjects such as art history or medicine, where you just need to remember facts, and the majority of facts are only loosely related to other facts. In learning languages, word tranlation pairs can be practiced to build a vocabolary. In all these examples (art history, medicine, languages), spaced repetition will still be a supplement to actually learning about e.g. context of the historical period, the interplay between different parts of an immune system, or learning language nuance, context and conversation.

But what about more conceptual subjects such as mathemathics and physics? The self-taught learner Scott Young[41] was initially skeptical of spaced repetition[42], but came around[43] and later posted his thoughts about SRS for conceptual topics[44]. He very clearly lays out the big challenge for using SRS in scientific and technical fields:

1. You could try to memorize Newton's 2nd law of motion, F = ma. But that is probably one of the least important parts. Having the mathematical insight and intuition into knowing what consequences such an equation have, what it really means, how it applies to the real world etc., are the important things.
2. The suggestion is, then, that you don't use SRS to memorize "facts" about physics or math. Instead you use them to prompt questions. So a flashcard wouldn't say "What is Newton's second law?" but,"Solve this set of differential equations."
3. But now the question is what do you solve? Do you solve the same question each time? That seems unfair. If I had a complicated question, I may not be learning to solve similar questions, but simply that the answer is "x = 7". We want to understand concepts, not just that a particular instance of a problem had a particular answer.
4. But if you want variety in your question, you could write a program that generates the problem with different numbers randomly.
5. This creates a new problem: writing the software to make flashcards with randomly generated values. It's not impossible, but it means you can no longer just create static content. There is software that does this, but it tends to be specialized, meaning it's a lot harder for DIY learners who want to learn methods that will work for any subject. You need some kind of scripting language to procedurally generate problem sets.

[41] Scott Young is an author and blogger known for "The MIT Challenge", where he attempted to learn MIT's 4-year computer science curriculum without taking classes in just a year purely by self-study and trying to optimize his study techniques (he has also done "The Year Without English", where he went to learn four languages in one year).

[42] https://www.scotthyoung.com/blog/2012/08/05/forgetting-is-good/

[43] https://www.scotthyoung.com/blog/2013/03/31/learning-methods/

[44] https://www.scotthyoung.com/blog/2014/11/07/srs-for-concepts

These are extremely good points, and also an opportunity to think out of the box, and what can be done with a very collaborative and deeply hierarchical flashcard system. Here are some of the opportunities that could solve these problems:

1. Since the hierarchy is build into the data structure composing the flashcards themselves, you could attach many little bonus questions on a single card. You could imagine that a class of students were assigned to add some fact about Newton's second law to the card, and the validity of these bonus questions could get approved by the instructor and/or through peers. For F=ma, this could be:

   - For the special case where the acceleration is constant, how does the formula integrate to velocity and positions functions v(t) and x(t)?
   - What happens when you combine this with Newton's law of universal gravity, what does this tell us about falling masses in vacuum?
   - Does this law apply to photons? If not, what law does instead?
   - Etc.

2. For conceptual subjects there is typically a natural distinction between theory and possible derivation / proof and theory, and application. So for every "theory card", there could be one of more links into "exercise cards" and vice versa. This even if you remember some equation or concept, you will then stay within context, and the next flashcard would be about applying the concept or vice versa. I think this staying within the same context for for periods of time is one of the key features that are missing from all the traditional SRS software.

3. Sometimes the context is just two cards: theory/exericse and vice versa.

Other times, the context could be a chain of cards, for example in describing an algorithm or data structure that solves a particular problem or have a particular set of desired properties. This would effecively be like going through your notes on the subject, but only revealing a little part at a time because you want to do active recall instead of merely re-reading and recognizing information.

4. The teacher could contribute with a set of flashcards that are just exercises, that are then automatically linked to the student's flashcard set both by automatic tag matching and simply by matching semester week. By matching keywords from the exercise solutions to existing flashards in the student's personal deck and the class' collective deck, the student could get hints towards the relevant theory without being given the full solution. The spaced repetition algorithm could be tuned to show the exercise cards less often than concept theory cards (since solving the same exercises more than once is generally less useful than solving new exercises).

5. Actually go thorugh the effort of making dynamic and interactive content and selling this as premium content in an in-app market place.

And interesting problem to be solved is to balance interleaved practice staying in context. I think this is best solved manually by setting a particular header level in the hierarchy is a natural unit, meaning that the system will not move to another subject until all sub-units of the current unit have been exposed to the user. As an example: perhaps you want to practice insertion, deletion and search algorithms for a particular data structure after first recalling the basic structure and properties of the data structure.

Also, every flashcard should contain a source. It is also important to emphasize that while some subjects are easier to summarize what completely into a set of notes, other subjects and endeavors, for example advanced machine learning more statistics, it is my personal experience that it is futile to attempt to make a complete set of notes because you would simply have to almost rewrite text book that you're reading because it some possible to skip too many details. Instead when should strive just to save those little important nuggets of information and not necessarily try to achieve completeness. Making notes in Flashcards should feel like a net benefit, not a chore. However where detail is lacking, one should always be able to go o the source, quickly by use of deep links.

11 Product Solution

I envision a collaborative learning platform where students can share insights on the lectures, reading and other course material, in the form of "information chunks", "highlights" or "take away points", which can also be made into flashcards easily. The notes can be single-sentence note from a book, the web or a lecture, that the student thought was important enough to remember. Or the notes can be fully fleshed out and structured notes.

11.1 Data structure

I think it's crucial to be able to look at the flashcard material either in hierarchical, organized form where it resembles organized course notes, where everything is in context. Especially in complex fields such as science and engineering, there are some kinds of knowledge that lends itself. The obvious solution to me is therefore notes and flashcards integrated, with flashcards getting their inherent structure and context from levels of headers in the notes.

The notes would be simple plain text using a flavor of Markdown[45] as markup language to allow flexible formatting, even including citation, math, footnotes etc. in certain flavors of the language. It is also a completely open plaintext format, similar to LaTeX. The Markdown syntax could be extended with a special tag to mark a section of the content as the answer for a question. The exact syntax isn't important, just the fact that it would be relatively straight to integrate note-taking with flashcard creation. This would greatly alleviate the classical problem of content duplication between notes and flashcards, and most importantly provide a natural organization and context of the flashcards for free. All notes are then hierarchical in nature. Every piece of content will belong to a header on a certain level, for example H1-H6 where H1 is the top level header (title), H2 is subtitle, etc.

This also alleviates the problem of context when reviewing flashcards; in conceptual subjects (math, physics etc.), it would be relatively straight forward to stay within the same context or "on-topic", by simply reviewing all flashcards within the same Markdown header level, either in random or sequential order. When reviewing the flashcard, the student could even be free to directly navigate to the note if he/she should choose, although active recall is the best method for long-term retention, as established earlier.

Finally, it should be possible to make internal links to other notes within the application.

11.2 User Interface

It is very important that the application focuses on fast content creation and the ability to offload snippets of text and thoughts quickly. It is not possible for me to come up with a perfect UI design all at once. The UI design process would instead be an elaborate, iterative process. But I have taken a stab at it, and sketched a few screens in the app as I imagined them in the first iteration.

11.2.1 Screen 1: Opening screen

Upon opening the app, the student will be met be a screen that looks roughly like Fig. 12. The text input is front and center, ready to capture any notes, which can be organized immediately by pressing any recent or starred notes. The rest of the UI is explained in the figure caption.

11.2.2 Screen 2: Course screen

The course screen (Fig. 13) shows a given week (or topic) within a course. It's easy to get an overview of all notes in the course, and see most upvoted content in the form of

[45] Markdown is a very easy to learn markup language that was originally made to make it easier to make formatted text for the web than using HTML, which involves lots of special tags. For example the syntax for writing boldface is `<string>this is bold</string>` in HTML and `**this is bold**` in Markdown.

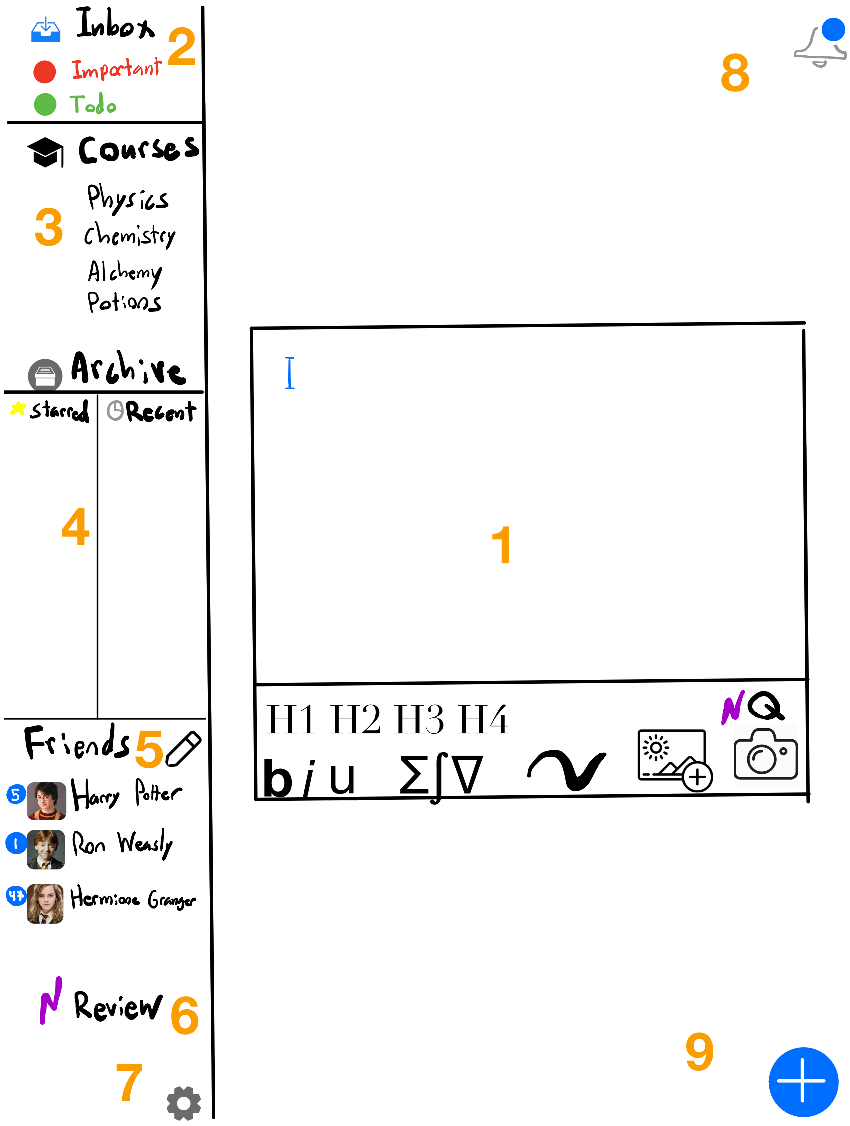

Figure 12: 1: Note input field, ready to write in startup, 2: Inbox where notes can be put temporarily, if not organized immediately, and a few default tags (here Important and Todo), 3: Course list, 4: Starred and Recent notes for quick navigation and organization of new notes, 5: Friends list, 6: Review flashcards button, 7: Settings, 8: Notifications, 9: Quick add note button

notes/flashcards and take-away points (highlights) and questions from the other students, as well as extra exercises with solutions.

11.2.3 Screen 3: Note screen

On the note screen (Fig. 14) we see an example of note content, including a question and flag from two fellow students. We also see related notes with own notes and a highly rated note from a peer. Some content has been marked and paired with questions, forming the basis of flashcards. The questions can be seen in the right-hand side, resembling the Cornell method note-taking style.[46]

11.3 Key features

- **Note-flashcard hybrid system** - Note-taking system where content can be marked and tagged for questions, effectively generating flashcards on the notes. We will henceforth call this structure "flashnotes"
- **Rich collaboration** - Ability to share flashnotes and copy, comment, upvote and suggest changes to other people's flashnotes.
- **Smart scheduling** - Tell the application the date of your exams, and it will optimize a review schedule for retention at exam date, then switch mode to long-term mastery after that.
- **Deep linking** - It should be possible (whenever technically possible) to create links straight to the source of a flashcard, whether that be specific pages in a PDF file or a specific time stamp in a YouTube video.

11.4 Bonus Features

Lastly I will mention some bonus features that would not be present in a first iteration of the product, but are very exciting possibilities to consider nonetheless.

11.4.1 Autotagging for Better Search and Flashcard Review

There are at least two organizations of notes that makes:

1. Organization according to how it was learning, i.e. course, week number, subject, etc.
2. Organization according to how it would be classified in an encyclopedia.

It would be possible to crawl through all Wikipedia pages, and construct a "knowledge graph skeleton", i.e. ignore the content but note how all the articles link to all the other articles. This could then be considered as a form of template, whereby arbitrary notes could then be automatically tagged and classified.

For instance, an note about "variance" in statistics could be tagged with tags `statistics`, `standard deviation`, and `expectation value` because concepts are linked to from the Wikipedia page on variance.

There would be at least two advantages if this could be done successfully:

1. It would enable even more powerful search in notes, if you want to know what notes you have on a particular overall subject, what else relates to it. A search field with auto complete suggestions that could filter all the notes and generate a word cloud could be a great way to explore what you know about a field or concept.
2. As we have already discussed, it would likely be beneficial to stay within context during flashcard review of complex concept-based subjects instead of reviewing cards in completely random order. During flashcard review, the note tags from the automatic tagging would provide the system with another measure of what concepts are related, presumably enchancing the flashcard review experience.

[46] https://theconversation.com/whats-the-best-most-effective-way-to-take-notes-41961

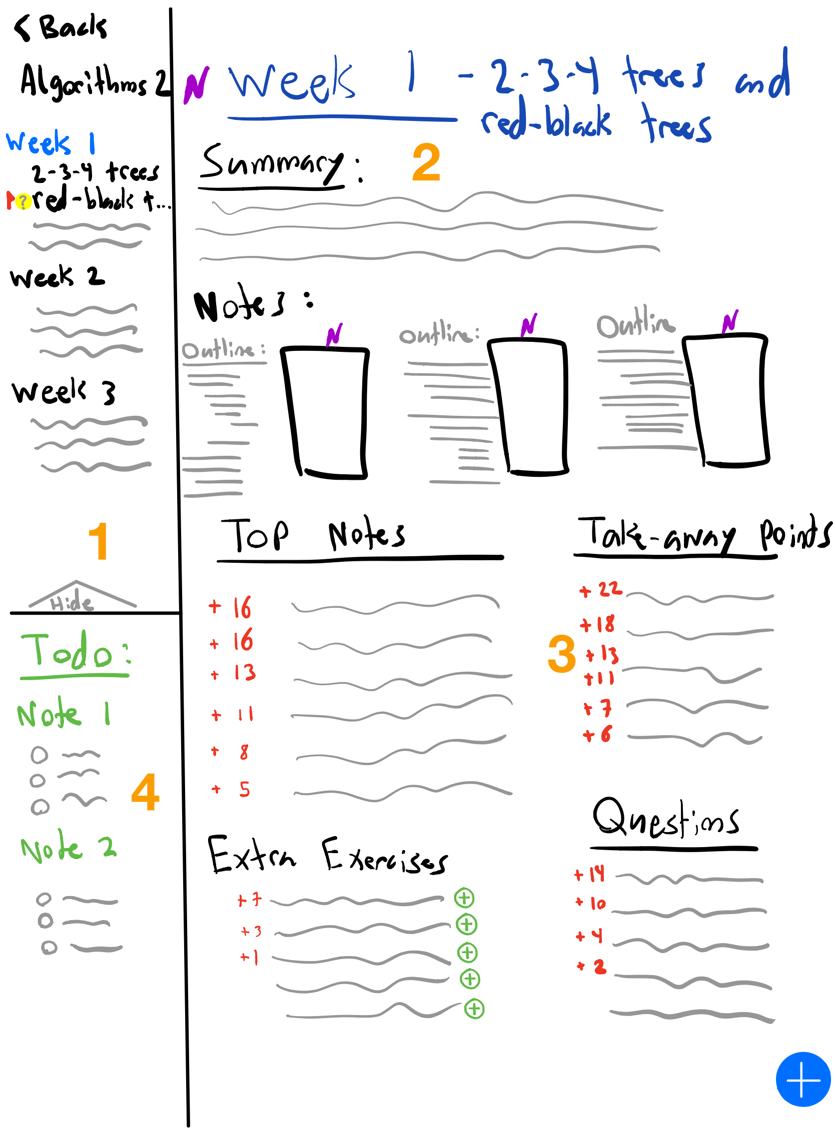

Figure 13: 1: Course overview and notes list, 2: Course week overview, including summary and notes with their outlines (i.e. table of contents), 3: Most upcated content and questions from the course for that particular week, 4: Todo list, i.e. an overview of all notes that have been tagged as incomplete somewhere, and what is missing

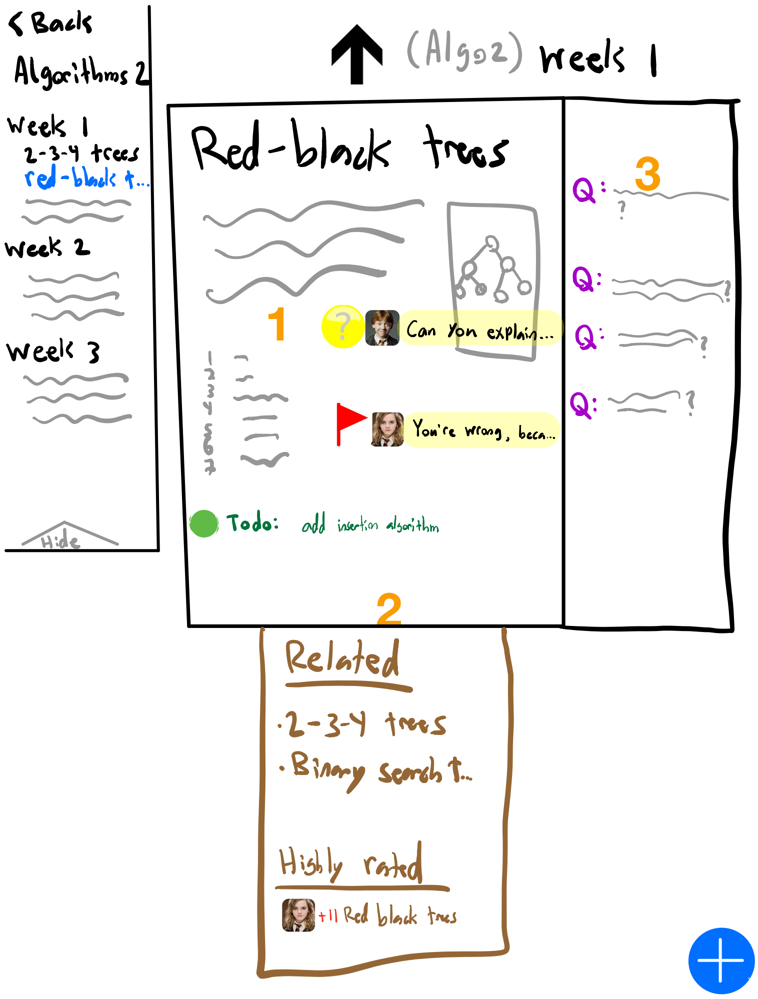

Figure 14: 1: Note content 2: Related notes in own library and highly rated peers3: Questions for content, forming the basis of flashcards.

11.4.1.1 Derived applications: recommendations for courses and review

Once the student knowledge has be tagged within some kind of objective tagging framework, it would in principle be possible to offer both course recommendations based on student interest and ability, as well as precise recommendations for concepts to review in preparation for upcoming courses.

11.4.2 Integrated homework system

One could imagine a simple system where students were assigned to for example:

- Find or invent a cool example where a recently learned concept is applied or could be applied.
- As homework, create an assignment or problem for other students to solve.
- Peergrade each other's flashcard decks.

11.4.3 Flexible TA employment

If a student for any reason display high skills in the course he is following to such a degree that he can for all practical purposes act as a TA for his fellow students, why not go the extra step and consider flexible hire of TAs through the system? There are many practical ways to handle this, and I have not thought it through yet. It could be that a student who earns enough "upvotes" or "reputation points" becomes eligible for payment as acting TA in the course if she commits to a certain number of homework assignment grading, or some hours of physical presence for actually acting as a TA etc. The possibilities are many. The point is, with a completely transparent system where all notes and flashcards are shared and discussed, it would be easy to identify the few very high performing students and actually compensate them if they wanted to do some extra work.

11.4.4 Using tags instead of folders

Tags are in general more flexible than folders since an object (here a note) could belong to multiple tags at the same time, whereas it can only be located in one folder. The note-taking app Bear[47] launched in 2016 drops the notion of folders entirely and uses tags only for organization.

11.4.5 Rich media and flashcard types

Flashnotes should support audio, video, hand drawing, file attachments and various structures such as mind maps (for a review of the *many* card types of FlashCram see (S. Colbran et al. 2014)).

11.5 Support from learning theories

11.5.1 Bloom's Taxonomy

Bloom's Taxonomy[48] is a classification scheme of learning objectives that can help an educator to design a course. The taxonomy breaks down learning objectives into six levels of objectives of increasing complexity that builds in one another, see Fig. 15

The most fundamental level is the bottom "Remember", which is the prerequisite for every learning activity above it. Even if a student has learned to understand, apply, analyze, evaluate and create, it all still hinges on the fact that the material can be remembered. One of the product solution's goals is to facilitate long-term retention, thus it supports all levels of

[47] http://www.bear-writer.com
[48] For an excellent description and examples of use see https://tips.uark.edu/using-blooms-taxonomy/
[49] For an excellent description and examples of use see https://tips.uark.edu/using-blooms-taxonomy/

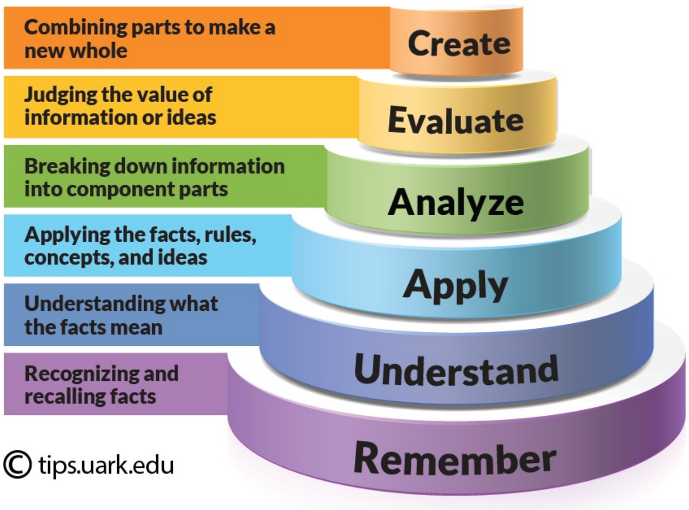

Figure 15: Bloom's Taxonomy[49].

Bloom's taxonomy *indirectly*. And as we saw in an earlier section "Self-testing", self-testing actually *directly* enhances all levels of learning objectives in Bloom's Taxonomy.

Furthermore, the suggestions in section "Integrated homework system" easily covers multiple levels of learning objectives in Bloom's Taxonomy.

11.5.2 The Case for Collaborative Co-creation

We have seen Peergrade take off as a successful EduTech startup from DTU with finding and support from the world-class incubator Y Combinator[50]. This is with good reason, because the case for aiding students with collaboration tools and peer-interaction that has only become possible with technology recently, is strong[51] (Prince 2004) . In their extensive review of digital flashcard tools for law students, (S. Colbran et al. 2014) discussed this aspect too:

> For many years academics have been designing learning activities and assessment tasks enabling students to *learn through making* [5] artefacts or engage in *learning by doing.* [6] These learning experiences are often informed by constructionism [7] and social views of learning. [8] Put simply, when we discuss and build an artifact, we learn something about it.
>
> (. . .)
>
> Digital students also crave peer review and interaction. Collaboration is at the heart of learning for them. Learning is a social phenomenon as well as a cognitive process. [28] By bouncing ideas off of each other, students can formulate their own opinions and drive the discussion themselves. They enjoy learning through discovery and discussion. [29] Their collaboration can either be in class, in person or virtual. [30] As a result, the professor no longer needs to be the sole and center point of learning; instead students have many resources from which to choose. Digital students often set up blogs for specific issues. They also e-mail and IM each other often (usually in the middle of class).

In their review of the online collaborative flashcard platform FlashCram, more feature similar to the ones I suggest, are mentioned:

[50] https://www.peergrade.io/blog/peergrade-goes-y-combinator/
[51] https://www.peergrade.io/pedagogy/

> Users may break and relink sequences of cards. New cards can be easily added into sequences or as entirely new topics. Old cards may be deleted or reorganised using a mind mapping construct. Data analytics can automatically follow the amended sequences providing useful diagnostic tools associated with student learning.

What (S. Colbran et al. 2014) sought and ultimately couldn't find (in 2014 at least) sound very close to my exact thoughts:

> There are a number of digital flashcard websites. A preliminary evaluation of these sites found no site that meet the authors' immediate requirements and could evolve as the authors' conception of digital flashcards developed within a learning model informed by a range of learning models including some embryonic ideas about connectionism, ie. representations of knowledge are distributed across a network of heterogeneous connections - learning being the ability of traverse and construct one's personal network (albeit shared between a group of people)

11.5.3 Metacognition and Self-regulation

(Huang 2017) writes that "Reflection is, however, intrinsically linked to metacognition and self-regulation, where there is ample evidence as to their importance to learning", the idea being that "through reflection, learners develop their ability to integrate the insights they gain into their learning/life experience so that they can make better choices and improve their learning". This makes sense, and at DTU we like evaluations a lot already, we do them twice every semester for every course. This could be another means to have the students reflect on what we are teaching them, every day.

(S. Colbran et al. 2014) also emphasize that flashcards promotes critical analysis, synthesis of information and self-reflection:

> Flashcards are commonly created and shared amongst people seeking to test their knowledge and memory. The process of construction of the flashcards promotes learning by doing, critical analysis and synthesis of information. Revision with flashcards promotes formative assessment and self-identification of misinterpretations and memory faults, which may in turn be corrected through self-reflection. Sharing of cards also affords the opportunity for peer review.

Being an regular and active creator of notes and flashcards forces you to take a very active stance in your own learning. The minimum information principles teach you to ask yourself "What are the core ideas of the book I'm reading?".

11.5.4 Flashcards Interacting With Various Learning Theories

The display of learning theories developed in the Holistic Approach to Technology Enhanced Learning (HoTEL) project reminds us of the range of learning theories available and serves as a nice overview,[52] see Appendix A.4.

(S. Colbran et al. 2014) proceeds to analyze how flashcards are used to support various learning activities derived from a wide range of learning theories depicted in the HoTEL framework. They have *a lot* and I have chosen to quote a subset that made especially good sense to me:

> - **Situated Learning** - Lave and Wenger [43] - whereby knowledge is co-constructed, situated in context and embedded in a social and digital environment. This theory sits within the discipline of social anthropology. Digital flashcards may be collaboratively constructed and shared with peers

[52] http://hotel-project.eu/content/learning-theories-map-richard-millwood

in a law course via the cloud-based FlashCram system. https://www.learning-theories.com/situated-learning-theory-lave.htmlSituated learning "takes as its focus the relationship between learning and the social situation in which it occurs".[1] https://en.m.wikipedia.org/wiki/Situated_learning

- **Constructivism** - Millwood, [45] von Glaserfeld [46] and Paiget [47] - the learner is no longer passive, but actively constructs knowledge. This theory sits within the disciplines of philosophy, cybernetics and anthropology. Digital flashcards can be easily incorporated into an assessment design whereby students create, document and share knowledge. The proliferation of shared digital flashcards available on the Internet on legal topics is testament to the ability of digital flashcards to be a tool active construction and sharing of knowledge.
- **Connectivism** - whereby 'knowledge is distributed across a network of connections to people and information - learning consists of the ability to construct and traverse those networks.' [49] This theory sits within the disciplines of Philosophy, Design, and Cybernetics. Students may create a network of digital flashcards by placing direct links in their digital flashcards to other digital resources or may include references to non-digital resources. The aim of this task is to make a network of resources, primarily to text, audio and video resources. Students may then share links to their packs of flashcards.
- **Expansive learning** - Engestrom [50] - This theory relates to 'The learning of new forms of activity as they are created, rather than the mastery of putative stable, well-defined, existing knowledge and skill'. [51] The degree of scaffolding provided by academics around the creation of digital flashcards may determine the boundaries of knowledge captured by digital flashcards. If for example, students are asked to develop flashcards on Restitution, the ambiguity of boundaries of the topic will enable students to explore the topic more excursively than with a very constrained topic.

Digital Flashcards align well with the following key concepts from HoTEL:

- **Communities of practice** - Lave & Wenger - Groups of people with a common interest learn together through interaction. Exercises may be designed to encourage collaborative digital flashcards to further a common purpose - examples of such cards include the Role-play card, Discussion card, Wiki card, Polling card etc.

12 Discussion and Reflection

12.1 Measure of Success?

When all is said and done, we have still not addressed one of the central points of the MIT paper (Subirana, Bagiati, and Sarma 2017) quoted in the introduction on the question "what do we forget?"

> On the first question, the vast majority of research focusses on retention of basic skills for less than a year. No retention of higher cognitive tasks has been found. For example, only the lower stage of Bloom's taxonomy [61] has been analyzed despite it having been initially introduced over 60 years ago. Surprisingly, the extensive literature on mastery has been largely ignorant of long-term effects. The focus has been on short term effects as if the goal was to master the subject for college education, i.e., to pass the exam and perhaps as a basis for subsequent courses in a particular subject line, but not to support a long-term career. I.e., none of the work reviewed so far addresses the question of what is it we want to

> measure in terms of college academics: is it the recall of basic concepts? Is it the ability to solve problems? Is it the ability to relate the subject to other forms of knowledge? Is it the ability to find relevant information about the subject when there is a need for it? Is it the ability to re-learn the subject? Is it the increase in the size of the cortex? All studies focus either on exam repetitions or on basic concept recall leaving a lot of room for speculation of what are the answers to the above questions. Richardson-Klavehn and Bjork [62] perform a very extensive review with about 300 references of the different ways to measure memory including free recall, cue recall and recognition. Unfortunately, here we are interested in very long term retention and all they discuss is short term memory (less than a year) – however, one should be able to use the same measure for short term and for long term experiments.

These are not trivial questions to answer, and will require years more research. However the last sentence is reassuring — all indications so far are that we *should* be able to use the same measure for short term and for long term experiments, and that long-term retention also follow an "Ebbinghaus forgetting curve".

12.2 Speculations on the Workings on Long-term Memory

(Subirana, Bagiati, and Sarma 2017) concluded:

> The single and most relevant finding of our research, one we can assert categorically (pending a full review), is that there is no single research experiment providing scientific evidence that academic content learned in college, subsequently-unused, is forgotten at a different speed than the one predicted by the Ebbinghaus curve: halving retention every two years.

Thus Ebbinghaus curve for long-term retention seems like a reasonable hypothesis until proven otherwise.

However the Ebbinghaus curve is by no means the only possibility on the workings of long-term memory. (Subirana, Bagiati, and Sarma 2017) concludes:

> At the functional level, our review has not found any model of forgetting that helps predict all the memory retention behaviors described and the realm of the unanswered covers basic issues such as whether the mechanism for retention differs depending on the interval. For example, our review is consistent with three broad operational models of long-term memory: 1. The first one, which we call the ECM model (Ebbinghaus Continuity Model) by which the same effects that are seen short term apply long term with different "parameters". This would explain why things are so easily forgotten and there should be a call to action in terms of finding optimal re-practice scheduling alternatives that extend the longevity of relevant learnings. Under this model, aspects like emotion, embodied cognition or grit simply modulate an underlying Ebbinghaus-like decay. 2. The second one is that there is a different type of memory mechanism that applies long-term which does not follow the Ebbinghaus curve, perhaps one that is more connected to emotions and less to short-term memory. Just like we have nuclear, gravitational and electric forces, each of which applies at a different level, we may have a "one-year" mechanism that applies to attain mastery but that there is a second one that applies in the long term. This second view may be consistent with some of the differences found in memory performance across experiments. The human brain may have adapted to a dual memory system, a four-season one-shot mastery-optimized cycle (that explains the perverseness of the short-term memory research and curriculum planning) and a longer-term memory system that operates under different norms retention-based where loyalty and group

values predominate and where mastery is not as important. 3. A third one would be that memory is alive, it behaves as a constantly changing organism that has a life of its own. It operates by guessing what we need from it and selectively forgets and evolves suggesting people forget what they learn in college because they sense it's useless beyond an exam, not because Ebbinghaus dictates it.

It will be very exciting to follow the research in this area as we hopefully get closer the which if the models above best reflect human memory. The scope of the SRS learning platform proposed in this report is to address the retention problem as good as possible based on the abundant up-to-1-year-retention-research, and assume that the effect will reflect into the long term (as preliminary research could indicate). Then adjustments can be made if new research on specifically long-term retention comes out with relevant findings.

12.3 Why Is Spaced Repetition Not Used in School?

(Dunlosky et al. 2013) gives two reasons why students don't use more efficient study techniques:

1. The teachers themselves are not schooled in them.
2. The educational system puts emphasis on teaching students critical-thinking skills and delivering content. "Less time is spent on teaching them how to learn. The result can be that students that do well in their early years, when learning is closely supervised, may struggle once they are expected to regulate their own learning in high school or college."

But why don't the universities push spaced repetition more? (Kang 2016) offers two explanations:

> Probably (at least) two major obstacles impede greater implementation of spaced practice in education.
>
> When deciding on what instructional techniques to use (and when to use them), many teachers default to familiar methods (e.g., how they themselves were taught; Lortie, 1975) or rely on their intuitions, both less than ideal: Our intuitions about learning can sometimes be plain wrong, and it would be a waste to overlook the growing evidence base regarding the effectiveness of various teaching or learning strategies. A possible solution is for teacher preparation to increase its focus on the science of learning (e.g., how the human mind learns, what factors influence learning, learning strategies, and their relative efficacy).
>
> The second major hurdle is conventional instructional practice, which typically favors massed practice. Teaching materials and aids (e.g., textbooks, worksheets) are usually organized in a modular way, which makes massed practice convenient. After presenting a new topic in class, teachers commonly give students practice with the topic via a homework assignment. But aside from that block of practice shortly after the introduction of a topic, no further practice usually follows, until a review session prior to a major exam. What this means for teachers deciding to incorporate spaced practice in their classrooms is that some planning is required. Complete overhaul of teaching practice may be difficult, but modifying homework assignments is probably an achievable target. The classroom-based studies described earlier (Rohrer et al., 2014; Rohrer et al., 2015) show how a small change in homework assignments—switching from having the practice problems in a given assignment on just one topic, to having a mix of problems pertaining to various topics appearing in each assignment—can dramatically improve mathematics learning.

Carolyn Vash put it more bluntly back in 1989 (Vash 1989, 1547):

> Education policy setters know perfectly well that spaced practice works better [than massed practice]. They don't care. It isn't tidy. It doesn't let teachers teach a unit and dust off their hands quickly with a nice sense of 'Well, that's done.'

I can see the historical reasons for why there has been too much inertia in the system a change towards practices recommendations by learning researchers. But I believe this is something we should change now. We can start small; some recommendations such as reordering the homework assignments should be easy to implement as a start. DTU have been willing to roll out Peergrade at DTU on a relatively large scale already - which is fantastic - but I think we should do more in the areas of interleaving and spaced repetition.

> At the end of the 19th century, William James (1899) exhorted teachers to encourage spaced practice in their students:
>
> *You now see why "cramming" must be so poor a mode of study. Cramming seeks to stamp things in by intense application immediately before the ordeal. But a thing thus learned can form but few associations. On the other hand, the same thing recurring on different days, in different contexts, read, recited on, referred to again and again, related to other things and reviewed, gets well wrought into the mental structure. This is the reason why you should enforce on your pupils habits of continuous application. (p. 129)*
>
> **The advice given over a 100 years ago is still completely applicable today, bolstered by the added weight of strong scientific evidence. My hope is that educators will embrace creative ways to foster spaced practice in and outside the classroom for the benefit of their students' learning.** (Kang 2016)

13 Conclusion

Research on study techniques and memory research are strongly supporting systems of *spaced repetition*. A *collaborative* spaced repetition system has been framed within various learning theories. I have made the case for why I note-taking is beneficial, and why trying to memorize anything is useful in the first place.

Some traditional problems with flashcards has been highlighted, most notably the problem of flashcards is their inherent tendency to become isolated facts instead of an interconnected web of knowledge. This problem is especially pronounced in STEM subjects. Solutions to this problem has been proposed in the form of a hybrid note-taking-flashcard system where understandings and insights from a course can be shared among course participants, who simultaneously can begin spread out their exam preparation in the whole semester, as well as having the means to remember the course material beyond the exam date.

A review of recent progress in optimizing spaced repetition scheduling for digital flashcards has also been reviews. We have gone through a discussion of the areas of still lacking research, mostly related to the workings of long-term memory (meaning timescales of more than a year), as well as possible reasons to why neither students nor institutions seems to be interested in spaced repetition and interleaving, despite the strong evidence. Finally, the specifics of the learning platform proposal have been presented, including data structure, key features and exciting possibilities that presents themselves as suggestions for unique bonus features.

We will end on a 30-year old quote that still rings true today:

> **Despite over a century of research findings demonstrating the spacing effect, however, it does not have widespread application in the classroom. The spacing effect is "a case study in the failure to apply the results of psychological research"** (Dempster 1988)

14 Further Reading

The following are the sources I found most useful and/or interesting during my research, and are consequently the most heavily cited in the report. I highly recommend reading any and all of them:

- (Branwen 2009) Already an "internet classic", a huge article focusing on spaced repetition and flashcards with *many* research paper citations as well as practical advice.
- (Subirana, Bagiati, and Sarma 2017) - From MIT Office of Digital Learning, an excellent review of the state of memory research based on a broad survey of hundreds of papers, especially lamenting the lack of memory research on long-term memory, i.e. time scales of more than a year.
- (Kang 2016) - From Dartmouth College Cognition and Education Lab, a very good overview of both self-testing, spaced practice, spaced repetition and interleaving, especially studies done on real-world class rooms, in particular STEM subjects.
- (Reddy et al. 2016) - The most technical of the papers and very clearly written. It focuses on the mathematical modeling of human memory, theoretical analysis, verification of memory models on big open datasets using maximum likelihood methods, application of queue theory to a Leitner-type spaced repetition system (dubbed a "Leitner Queue Network"), verification of this Leitner Queue Network of by simulations, and finally usage of Amazon Mechanical Turk to for verification of the Leitner Queue Network.

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A Appendix

A.1 Front Page Logo Explanation

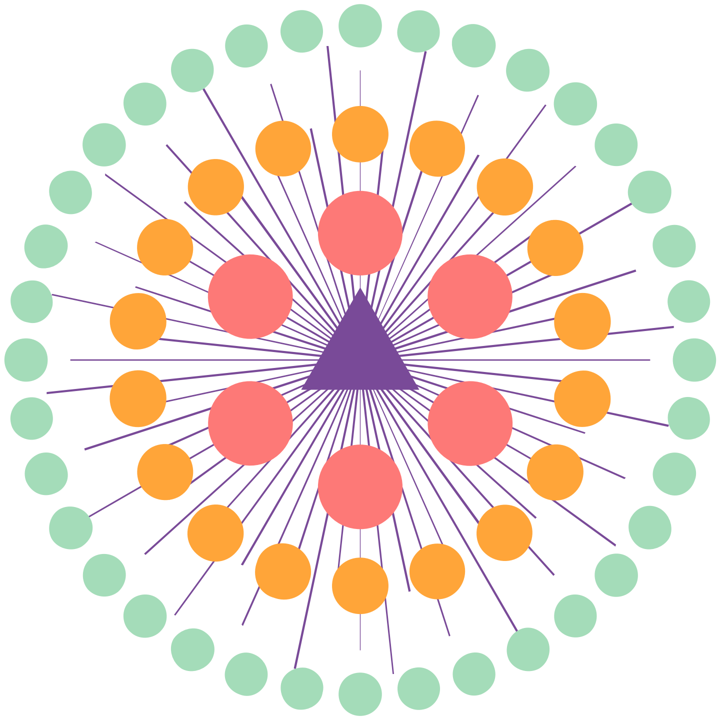


Figure 16: Front page logo.

- **The purple triangle** in the middle symbolizes the individual student who is learning.
- **The red inner circle** symbolizes the student's immediate *friend circle* who is participating in the same learning course / learning activity.
- **The orange middle circle** symbolizes *all* the students who is participating in the same learning course / learning activity.
- **The green outer circle** symbolizes the rest of the world.
- **The purple rays** emanating from the self in the middle symbolizes thought activity and understanding from the student.

The whole symbol is meant to symbolize how every single student can affect and collaborate with the whole course, and even the whole world during their learning activities, instead of mostly interacting with their closest friends.

A.2 Early prototype

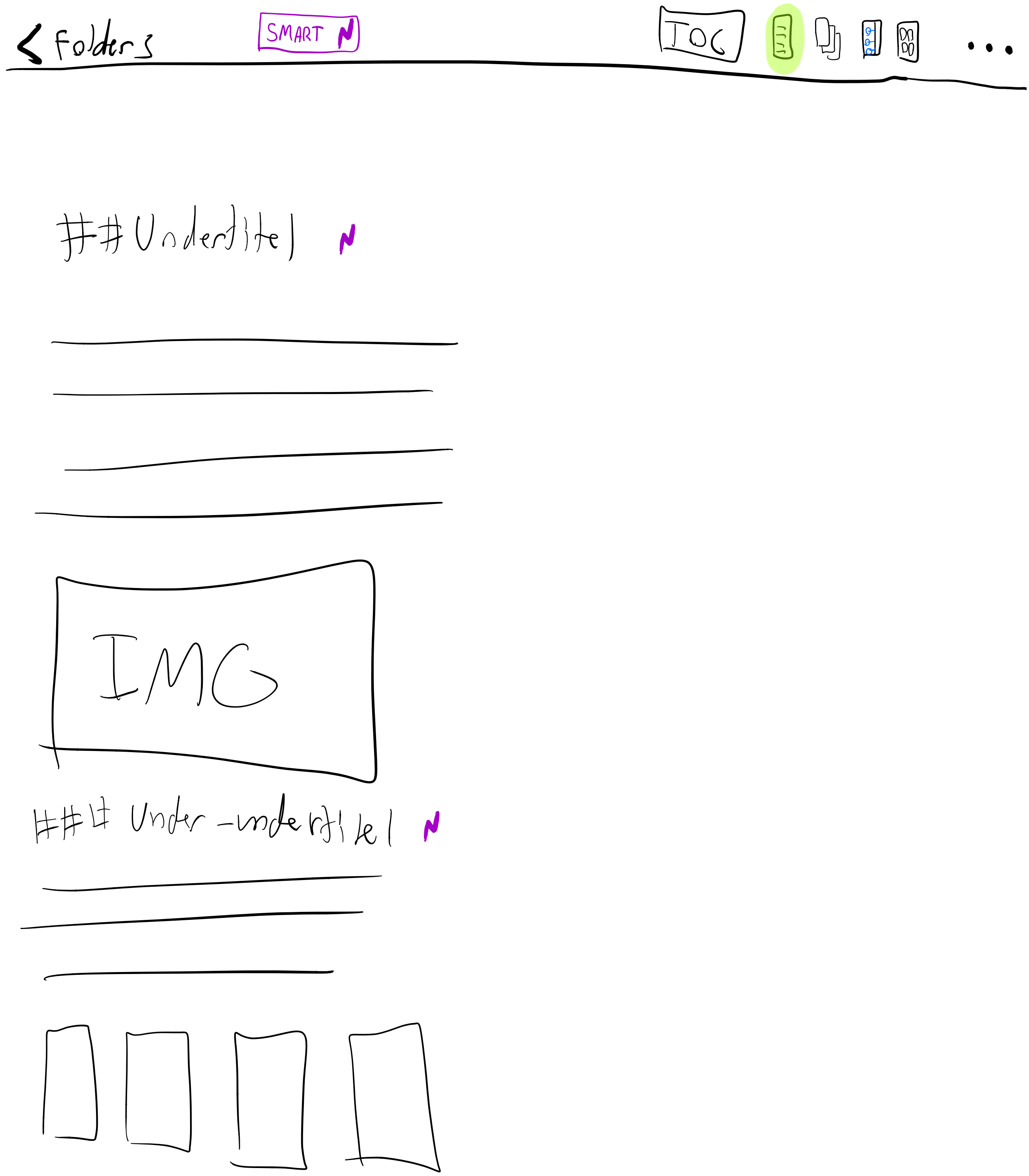
The following prototype developed during the course was inspired by Microsoft OneNote for interface and organization features, and then added flashcard capabilities on top.

EARLY PROTOTYPE (October 2017)

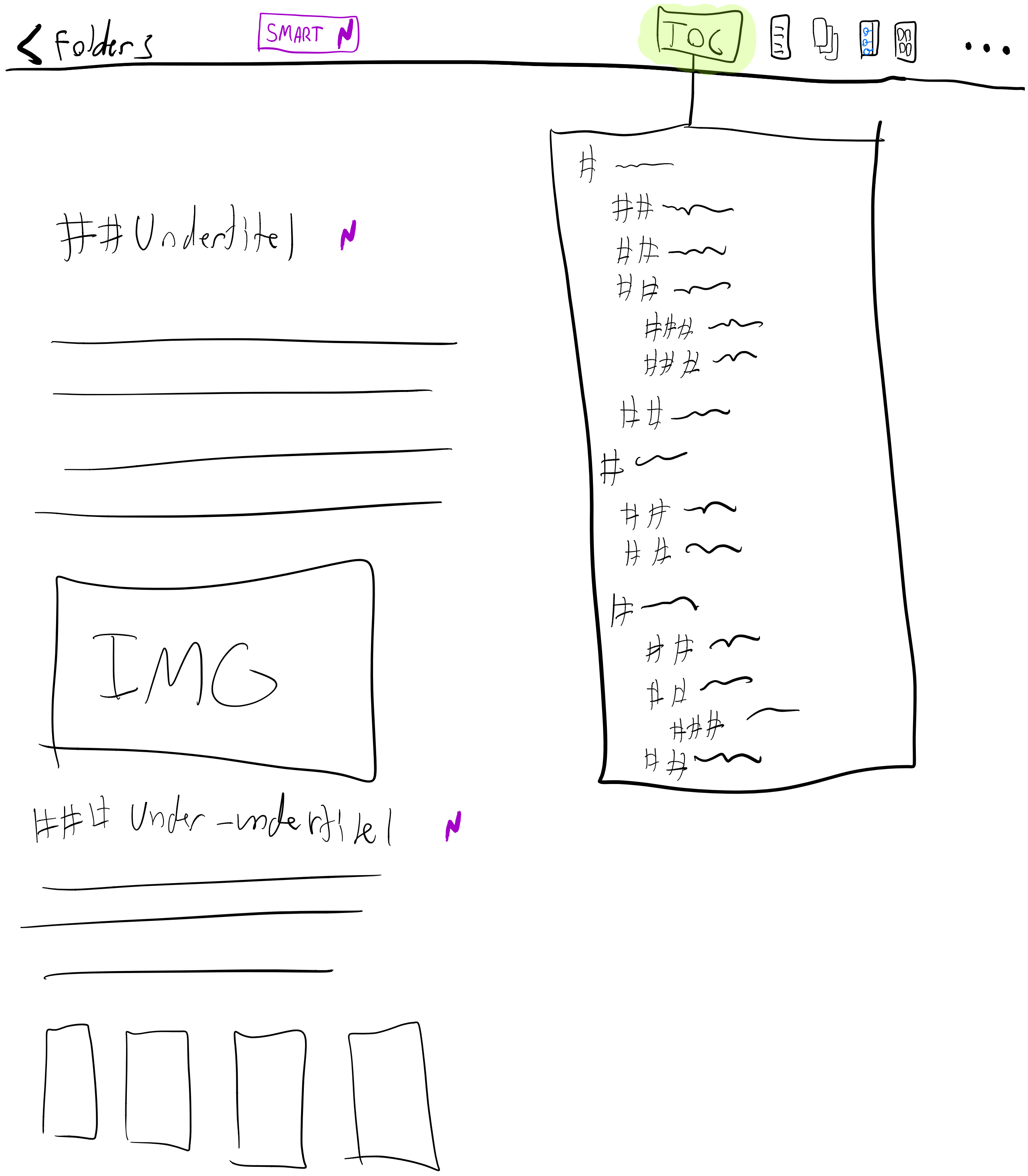
Flashnote N

Presentation

EARLY PROTOTYPE (October 2017)

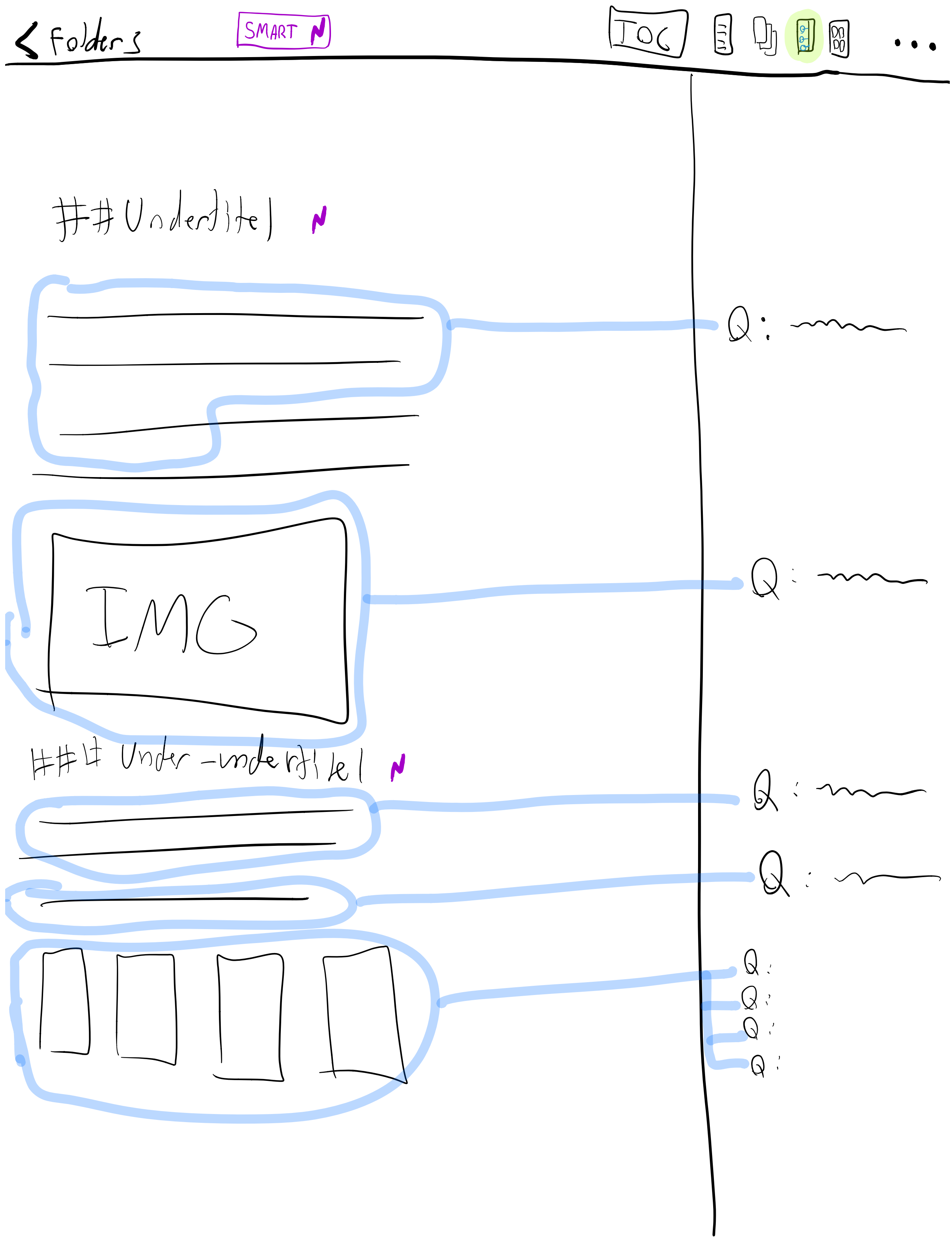


EARLY PROTOTYPE (October 2017)



EARLY PROTOTYPE (October 2017)

EARLY PROTOTYPE (October 2017)



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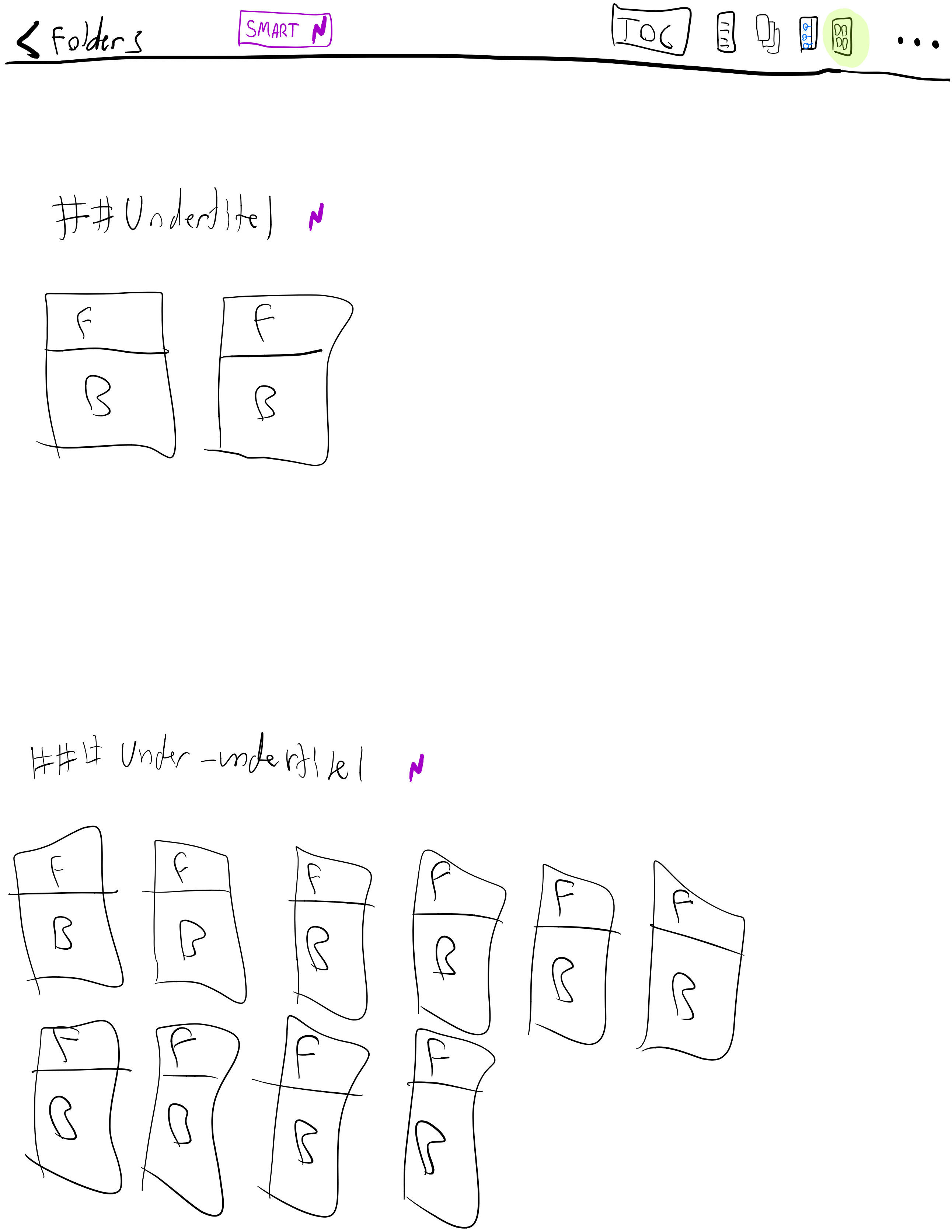

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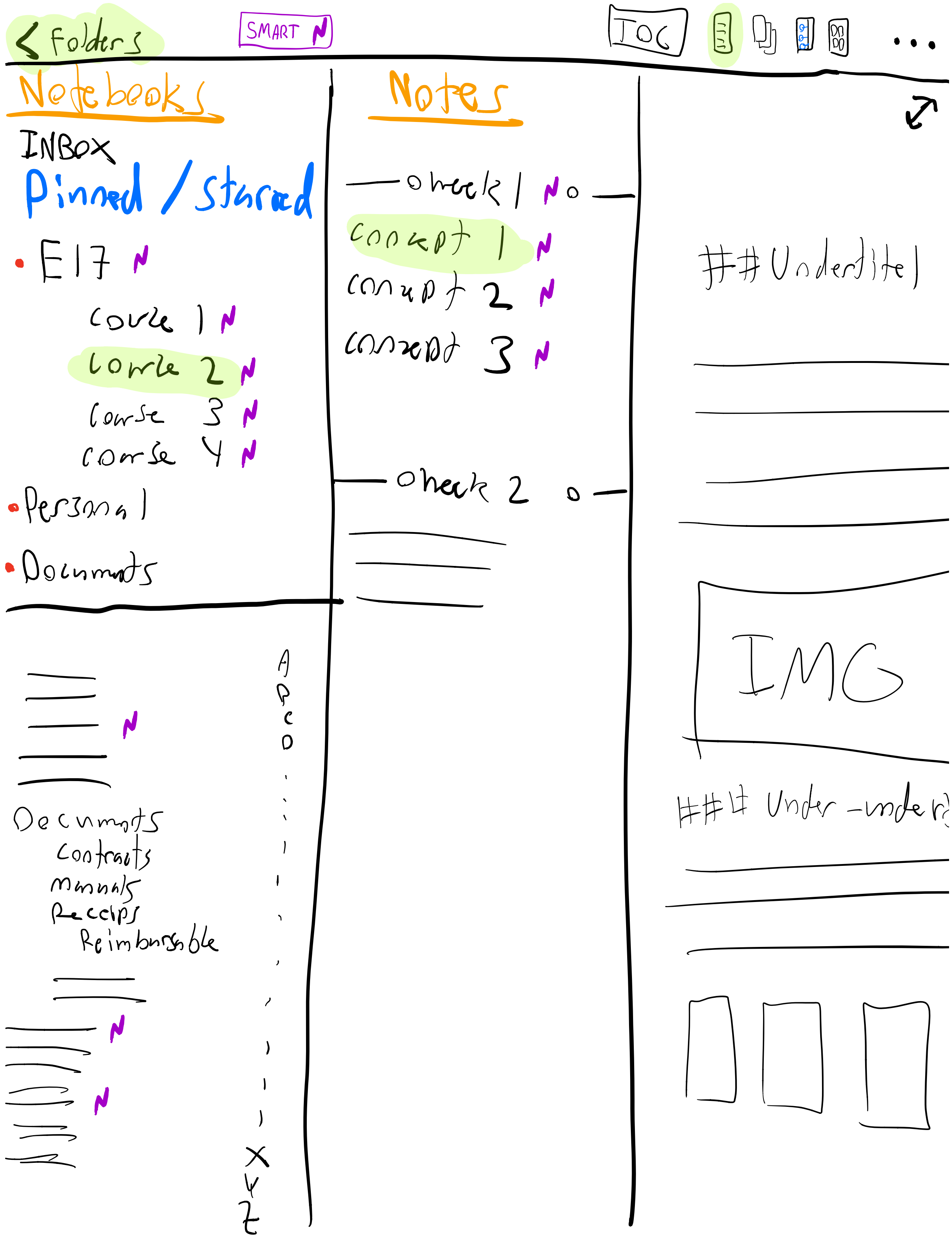
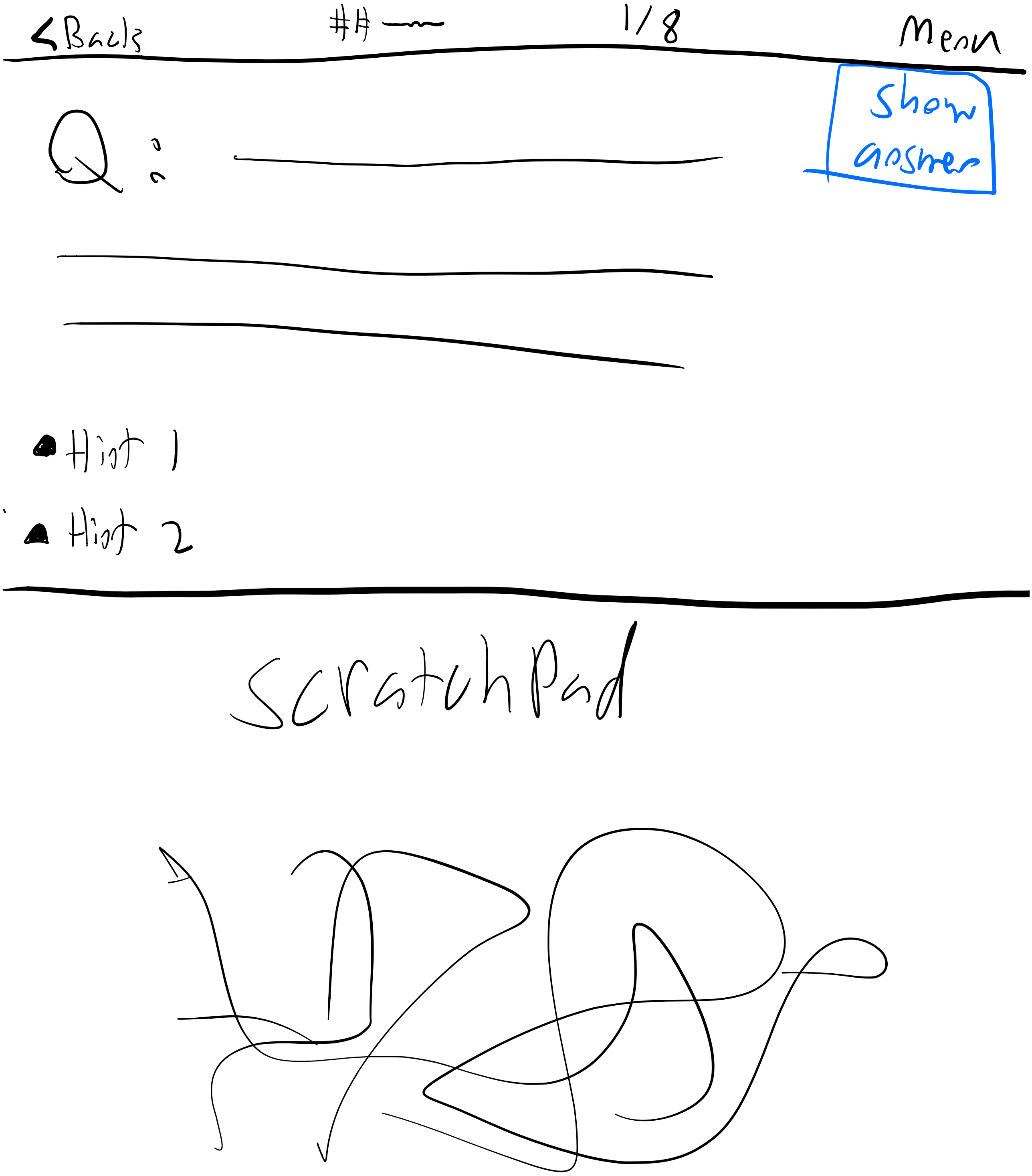


EARLY PROTOTYPE (October 2017)



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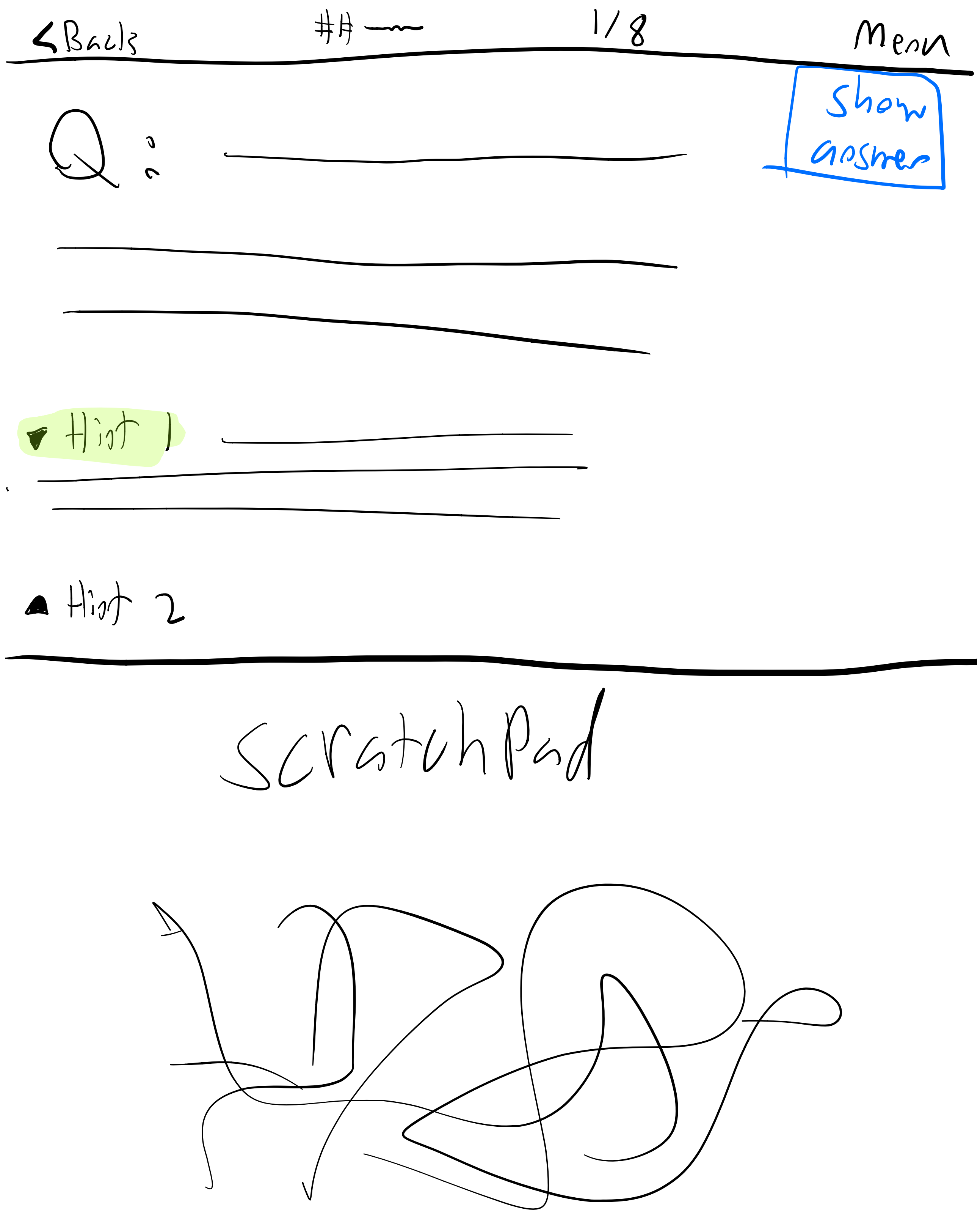

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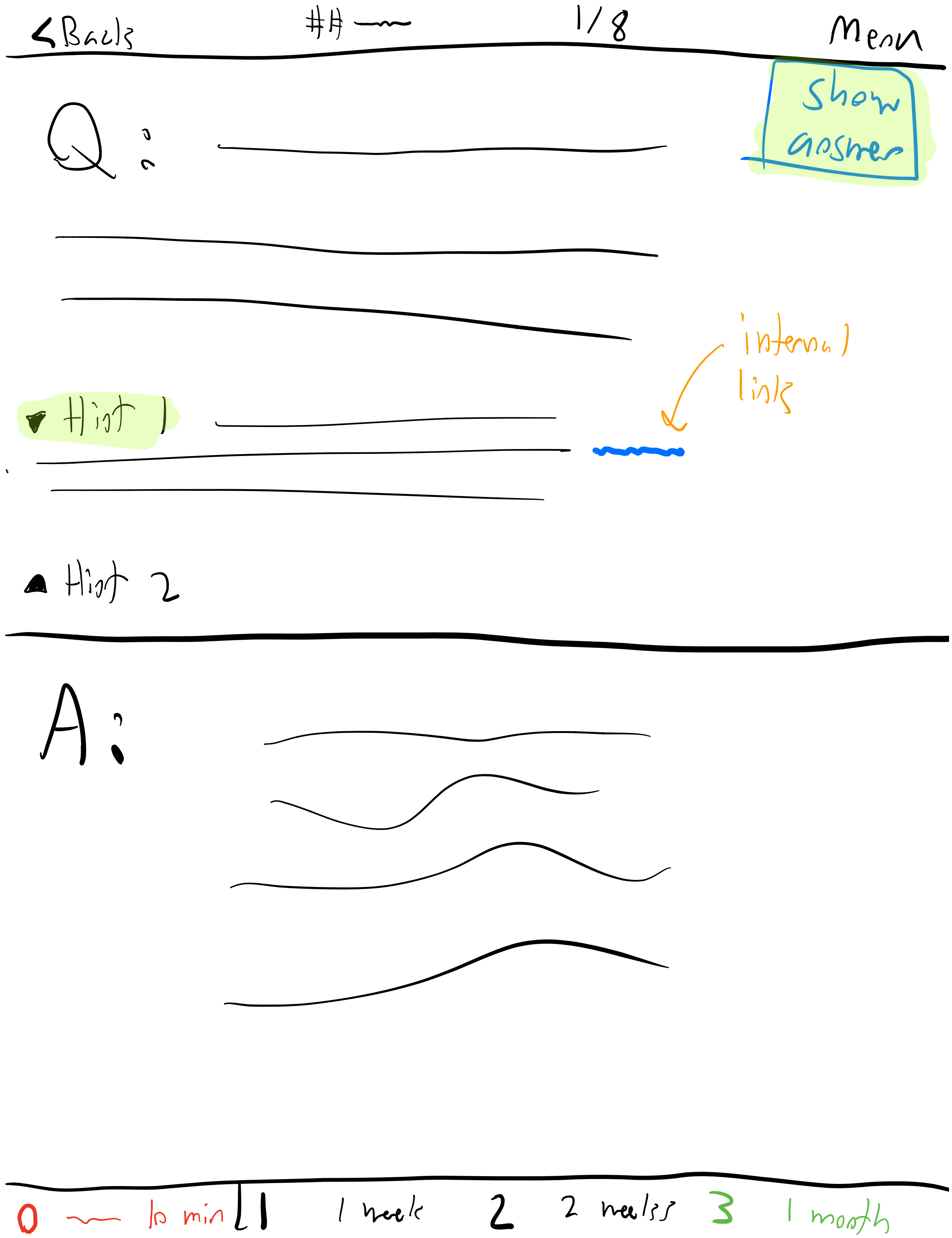


EARLY PROTOTYPE (October 2017)

Extra features

- Camera photo of physical paper —> Edible handwriting objects (PDFs?)
- Interactive objects —> running code
- Possibility of having interactive textbooks, i.e. professors making notes / flashcard decks for students
- Real-time collaboration on the same doc
- Ultimate goal / business model: Professionally made quizzes and exercises with dynamic content

Quickly Show

Goodnotes (thumbnail view)

Anki (practice window)

HackMD
https://hackmd.io/features?both#image-upload

Simulation of SRS Vs. Traditional Review
https://youtu.be/ai2K3qHpC7c

A.3 Spaced and Interleaved Practice in the Classroom

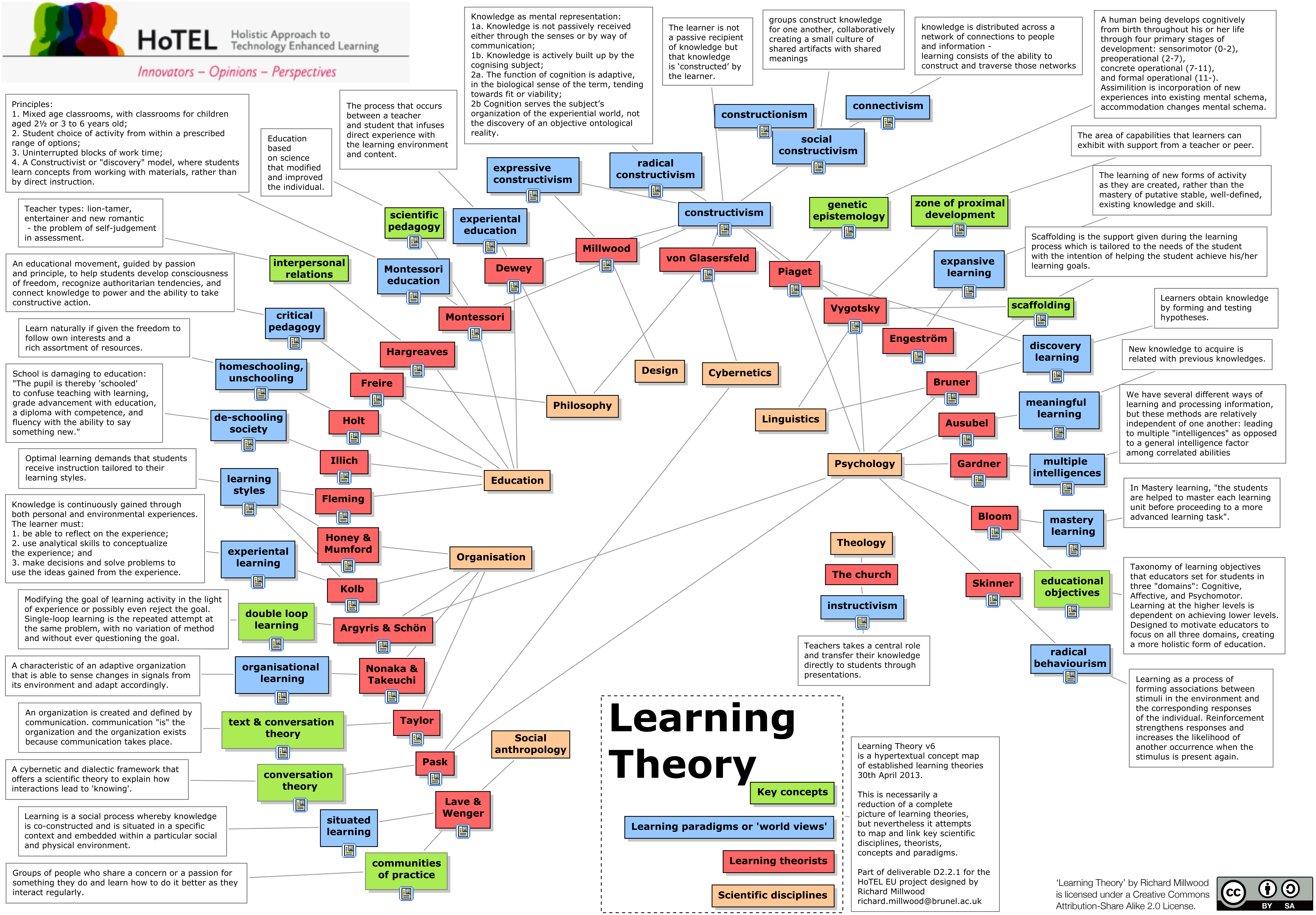
The following is a quoted section of paper (Kang 2016), emphasis added by me:

> Although most studies on spaced or interleaved practice have been conducted in laboratory settings (for better control over extraneous variables), students in actual classrooms can benefit from instructors using these learning strategies (e.g., Carpenter et al., 2009; Sobel, Cepeda, & Kapler, 2011). A few studies were conducted not only in real-world educational settings but also in the context of a regular curriculum (i.e., instructional manipulation on course content).
>
> In one classroom-based study, the mathematics homework assignments for seventh-grade students were manipulated across 9 weeks (Rohrer, Dedrick, & Burgess, 2014). Ten mathematics assignments were given out over that period, each consisting of 12 practice problems. For topics assigned to blocked practice, all 12 problems in a single assignment would pertain to that one topic (and no other assignment would feature that kind of problem). For topics assigned to interleaved practice, only the first four problems in the assignment would belong to the current topic; the other eight problems in the assignment would cover previous topics; also, the remaining eight practice problems pertaining to the current topic (of the first four problems) would be distributed across future assignments. That is, the total number of practice problems devoted to each topic was equal across the blocked and interleaved conditions (12 practice problems per topic). The only difference was whether all 12 problems on a given topic were completed in one assignment or whether they were spread out across multiple assignments (and therefore interleaved with other types of problems). On a surprise test containing novel problems (on the same topics), given 2 weeks after the final homework assignment, the students were substantially better at solving the types of problems that had been practiced in an interleaved manner than those under blocked practice.
>
> Interleaving has strong benefits even when the problem types were quite different (Rohrer et al., 2014), compared with the earlier studies on mathematics problem solving (e.g., Rohrer & Taylor, 2007). **Enhanced discrimination (learning to differentiate the various types of problems) is not the only explanation for the interleaving advantage. During interleaved practice, switching among different problem types may strengthen the association between a problem type and its strategy, which promotes successful problem solving. With blocked practice, on the contrary, as all the problems require the same strategy, the student needs only focus on executing a given strategy repeatedly, which might not be as effective in reinforcing the association between a problem type and its strategy (Rohrer et al., 2014; see also Rohrer, Dedrick, & Stershic, 2015).** A similar study conducted within a college engineering course found that spacing out the practice problems on a given topic over 3 weeks produced better performance on the midterm and final exams than having practice problems on a given topic assigned only during the week that the topic was taught in class, which was the standard practice (Butler, Marsh, Slavinsky, & Baraniuk, 2014).
>
> **The studies described above are notable for two reasons. First, they were conducted within a regular class (middle school mathematics, college-level engineering). Given that classroom-based studies tend to be more "noisy," due to the lack of control over many variables (e.g., Greene, 2015), the observed effect of spacing/interleaving is impressive. Second, the instructors taught the classes as they normally would have—the topics covered, the lecture content, and the**

assessments generally remained the same—suggesting that a radical overhaul of teaching practice may not be necessary. Something as simple as reorganizing the homework assignments may be sufficient to produce sizable gains.

A.4 HoTEL Learning Theory Overview

The following display of learning theories was developed in the Holistic Approach to Technology Enhanced Learning (http://hotel-project.eu/content/learning-theories-map-richard-millwood).


HoTEL
Holistic Approach to Technology Enhanced Learning
Innovators – Opinions – Perspectives
Learning Theory
Key concepts
Learning paradigms or 'world views'
Learning theorists
Scientific disciplines
Principles:
1. Mixed age classrooms, with classrooms for children aged 2½ or 3 to 6 years old;
2. Student choice of activity from within a prescribed range of options;
3. Uninterrupted blocks of work time;
4. A Constructivist or "discovery" model, where students learn concepts from working with materials, rather than by direct instruction.
Education based on science that modified and improved the individual.
The process that occurs between a teacher and student that infuses direct experience with the learning environment and content.
Knowledge as mental representation:
1a. Knowledge is not passively received either through the senses or by way of communication;
1b. Knowledge is actively built up by the cognising subject;
2a. The function of cognition is adaptive, in the biological sense of the term, tending towards fit or viability;
2b Cognition serves the subject's organization of the experiential world, not the discovery of an objective ontological reality.
The learner is not a passive recipient of knowledge but that knowledge is 'constructed' by the learner.
groups construct knowledge for one another, collaboratively creating a small culture of shared artifacts with shared meanings
knowledge is distributed across a network of connections to people and information - learning consists of the ability to construct and traverse those networks
A human being develops cognitively from birth throughout his or her life through four primary stages of development: sensorimotor (0-2), preoperational (2-7), concrete operational (7-11), and formal operational (11-). Assimilation is incorporation of new experiences into existing mental schema, accommodation changes mental schema.
The area of capabilities that learners can exhibit with support from a teacher or peer.
The learning of new forms of activity as they are created, rather than the mastery of putative stable, well-defined, existing knowledge and skill.
Scaffolding is the support given during the learning process which is tailored to the needs of the student with the intention of helping the student achieve his/her learning goals.
Learners obtain knowledge by forming and testing hypotheses.
New knowledge to acquire is related with previous knowledges.
We have several different ways of learning and processing information, but these methods are relatively independent of one another: leading to multiple "intelligences" as opposed to a general intelligence factor among correlated abilities
In Mastery learning, "the students are helped to master each learning unit before proceeding to a more advanced learning task".
Taxonomy of learning objectives that educators set for students in three "domains": Cognitive, Affective, and Psychomotor. Learning at the higher levels is dependent on achieving lower levels. Designed to motivate educators to focus on all three domains, creating a more holistic form of education.
Learning as a process of forming associations between stimuli in the environment and the corresponding responses of the individual. Reinforcement strengthens responses and increases the likelihood of another occurrence when the stimulus is present again.
Teachers takes a central role and transfer their knowledge directly to students through presentations.
Teacher types: lion-tamer, entertainer and new romantic - the problem of self-judgement in assessment.
An educational movement, guided by passion and principle, to help students develop consciousness of freedom, recognize authoritarian tendencies, and connect knowledge to power and the ability to take constructive action.
Learn naturally if given the freedom to follow own interests and a rich assortment of resources.
School is damaging to education: "The pupil is thereby 'schooled' to confuse teaching with learning, grade advancement with education, a diploma with competence, and fluency with the ability to say something new."
Optimal learning demands that students receive instruction tailored to their learning styles.
Knowledge is continuously gained through both personal and environmental experiences. The learner must:
1. be able to reflect on the experience;
2. use analytical skills to conceptualize the experience; and
3. make decisions and solve problems to use the ideas gained from the experience.
Modifying the goal of learning activity in the light of experience or possibly even reject the goal. Single-loop learning is the repeated attempt at the same problem, with no variation of method and without ever questioning the goal.
A characteristic of an adaptive organization that is able to sense changes in signals from its environment and adapt accordingly.
An organization is created and defined by communication. communication "is" the organization and the organization exists because communication takes place.
A cybernetic and dialectic framework that offers a scientific theory to explain how interactions lead to 'knowing'.
Learning is a social process whereby knowledge is co-constructed and is situated in a specific context and embedded within a particular social and physical environment.
Groups of people who share a concern or a passion for something they do and learn how to do it better as they interact regularly.
expressive constructivism
radical constructivism
constructionism
social constructivism
connectivism
constructivism
scientific pedagogy
experiential education
Millwood
von Glasersfeld
Piaget
genetic epistemology
zone of proximal development
expansive learning
scaffolding
Vygotsky
Engeström
discovery learning
Bruner
meaningful learning
Ausubel
multiple intelligences
Gardner
Bloom
mastery learning
educational objectives
Skinner
radical behaviourism
Psychology
Theology
The church
instructivism
Linguistics
Cybernetics
Design
Philosophy
interpersonal relations
Montessori education
Dewey
Montessori
critical pedagogy
Hargreaves
Freire
homeschooling, unschooling
de-schooling society
Holt
Illich
Education
learning styles
Fleming
Honey & Mumford
Organisation
experiential learning
Kolb
double loop learning
Argyris & Schön
organisational learning
Nonaka & Takeuchi
text & conversation theory
Taylor
Social anthropology
conversation theory
Pask
situated learning
Lave & Wenger
communities of practice
Learning Theory v6 is a hypertextual concept map of established learning theories 30th April 2013.
This is necessarily a reduction of a complete picture of learning theories, but nevertheless it attempts to map and link key scientific disciplines, theorists, concepts and paradigms.
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