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CBMM Memo No. 068

June 20, 2017

ON THE FORGETTING OF COLLEGE ACADEMICS: AT “EBBINGHAUS SPEED”?

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Abstract

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.



This work was supported by the Center for Brains, Minds and Machines (CBMM), funded by NSF STC award CCF-1231216.

⁴ Part of this research was done while Prof. Subirana was a Visiting Scholar at the MIT Office of Digital Learning

“Six verses of a poem require for learning not only three times as much as two but considerably more than that.”

Ebbinghaus (1885)

“We find that our working stock of ideas is narrowly limited, but that the mind continually recurs to them in conducting its operations, therefore its tracks necessarily become more defined and its flexibility diminished as age advances.”

Francis Galton, F.R.S. (1879)

Keywords: Forgetting. Memory Retention. College Academics. Ebbinghaus. Memory.

1 INTRODUCTION⁵

How important are undergraduate college academics after graduation? How much effort do we put in understanding retention of learning after graduation, and how is this reflected on the job market? When Steve Balmer, arguably the highest paid employee ever, attended his alma matter for a guest lecture⁶ entitled “Most of what I needed to know I learned at Harvard” stated in the first slide: “... And it wasn’t in the classroom”. In general, college academics taught in the classroom don’t seem to be recognized explicitly by public market indicators. As an example, MIT was ranked number one in the world by US News Report in the latest ranking available⁷, however taking a closer look at the ranking methodology one can see it does not include any metric of what students retained from the classroom,. In fact, all major market ranking methodologies consistently lack any objective measure of student college academic retention ([MIT office of the provost 2012]⁸). Google, the best company to work for according to Fortune⁹, has reported to the New York Times¹⁰ 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. For example, 9 MIT freshman physics students majoring in either physics, aeronautics & astronautics or mechanical engineering, were retested in their senior year on the same subject and performed worse on average and only one, the second worst performer¹¹, did significantly better (20% better) in the subject at graduation [1]. Could it be that Steve Balmer, shortly after leaving Harvard forgot all academics he had been taught?

In the last decade of the XVIII century the interest in how memory worked followed the discovery of neurons by Santiago Ramón y Cajal [2] and was addressed by a number of researchers from different angles [3], [4], [5]. In memory retention, seminal research was published by Ebbinghaus in the period 1880-1885 [5]. After doing various recall tests using himself as a subject, he postulated memory retention follows an exponential forgetting curve with a decay rate whose length depends on the task. Many studies on autobiographic memory have taken place since then, and results show decay following similar patterns. Can it be that remembering academic content follows a similar model?

Taking the findings of the Ebbinghaus studies under consideration, we focused our efforts on identifying whether there is any evidence against the following conjecture: “Academic content retention follows the Ebbinghaus forgetting curve with a decay of about 50% every two years”. We are concerned with identifying research providing two warrants: an academic-related performance metric and a related memory retention metric estimated after a period extending over two years at least.

⁵ Results from this research were originally presented at a CBMM talk: <https://www.youtube.com/watch?v=DdMII6R1MJ0>

⁶ <https://www.youtube.com/watch?v=7lhKF6MECs> (accessed Feb 2017)

⁷ <http://news.mit.edu/2016/us-news-top-rankings-mit-graduate-programs-engineering-business-0316> (accessed Feb 2017)

⁸ http://web.mit.edu/ir/rankings/Ranking_Methodology_Nov2012.pdf, (accessed Feb 2017)

⁹ <http://fortune.com/best-companies/> (accessed Feb 2017)

¹⁰ <http://www.nytimes.com/2013/06/20/business/in-head-hunting-big-data-may-not-be-such-a-big-deal.html> (accessed Feb 2017)

¹¹ The student was at 40 on a renormalized to 100 scale, and performed at 100 at graduation. It can be argued this is an outlier or simply had a bad day in Freshman physics (or lucky at graduation).

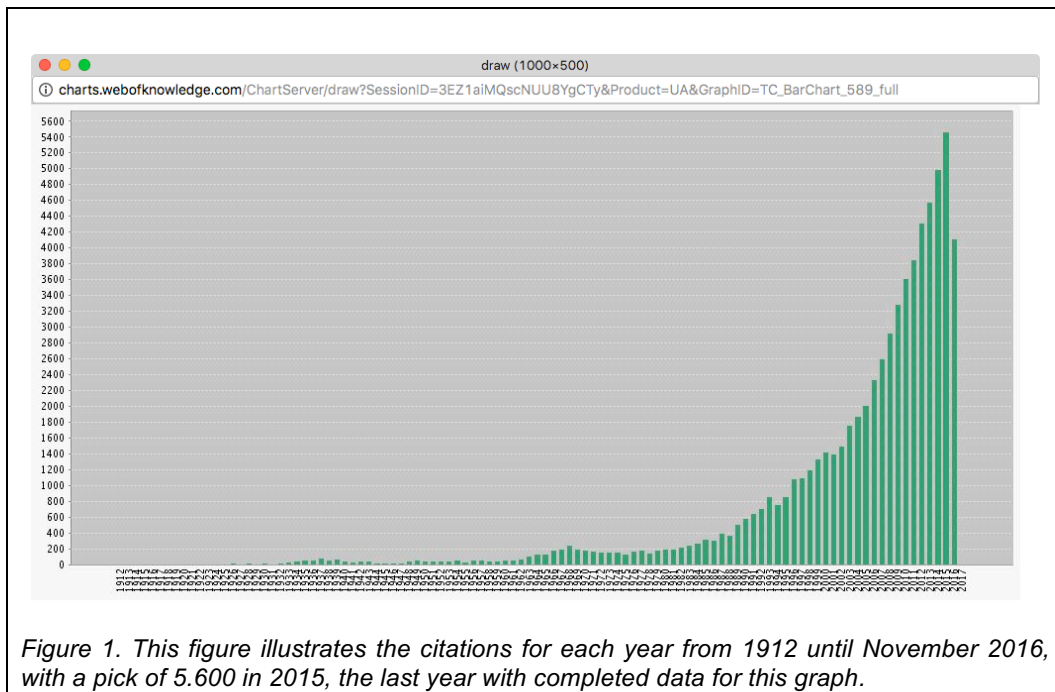
To put things in context and to illustrate the relevance of our research goals with an example, if this universal law is confirmed, it would mean that when a US doctor starts performing, retention is less than 5% of unused freshman academics. Introductory biology may probably have been reviewed and hence significantly better retained than linear algebra. The level of retention of algebra, instead, would be of such a level that only basic concepts may be remembered while the ability to do any abstract operations is completely lost at that stage – and again, this remembering of basic concepts would disappear almost completely a few years into practice, hence, why studied it in the first place?

In section 2 we review the methodology used, in section 3 the findings of this preliminary review and we conclude in section 4 with some conjectures and suggestions for future research. A version of the research presented here will be presented at a conference [6].

2 METHODOLOGY

2.1 Description of the review methodology used

The review methodology used consisted on two searches for papers citing Ebbinghaus 1885's paper, one search in Google Scholar and one in the Web of Science. The two resulting lists were sorted into three groups, papers published in 2014-2016, papers with high-impact (cited over 100 times), and the rest. The papers from the first two groups, approximately 100, were then split among two of the authors in the author list for further analysis. Each author perused fifty papers, and when appropriate referenced papers also, in order to identify the retention interval of the reported experiments and the disciplinary domains researched. All papers were classified based on the relevance to either academic learnings or long-term retention (long-term was over two years), based on the application domains (STEM, language, autobiographical, other non-academic) and based on the subject types (students, animals, others). Papers including experiments falling in several categories were included in all.



2.2. Discussion of the methodology

The choice of a methodology focused on finding papers referencing Ebbinghaus is based on the assumption that if there is any research relevant to learning retention, it would either reference the Ebbinghaus work or it would be referenced by one of the papers that reference Ebbinghaus. This resulted in a number of reviews on the subject that did not contradict any of our conjectures, which strengthen our belief that we have reached all major types of research on the subject.

2.2 Study limitations

Despite conducting the search using two of the most widely popular scholar databases, we understand there is the risk of missing relevant papers in the case they might not reference Ebbinghaus, or in the case they might not be references in any of the papers analyzed in this data set.

3 RESULTS

3.1 We forget at the “speed of Ebbinghaus”

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. By scientific evidence we mean an experiment that has been at least repeated once, is rigorous, repeatable and relevant. A small number of papers identified challenging the forgetting curve did not appear to be providing enough evidence in order to facilitate repeatability of the experiments, and in the process, leaved many questions unanswered as we will see when we present the handful of papers in this category. On the other hand quite a lot of experiments, presenting evidence about forgetting at Ebbinghaus speed were often presented rigorously and appeared replicable – most, however, were short-term interval experiments testing learning up to some weeks or months after initial learning occurred.

3.2. Universal Evidence in the Animal Kingdom

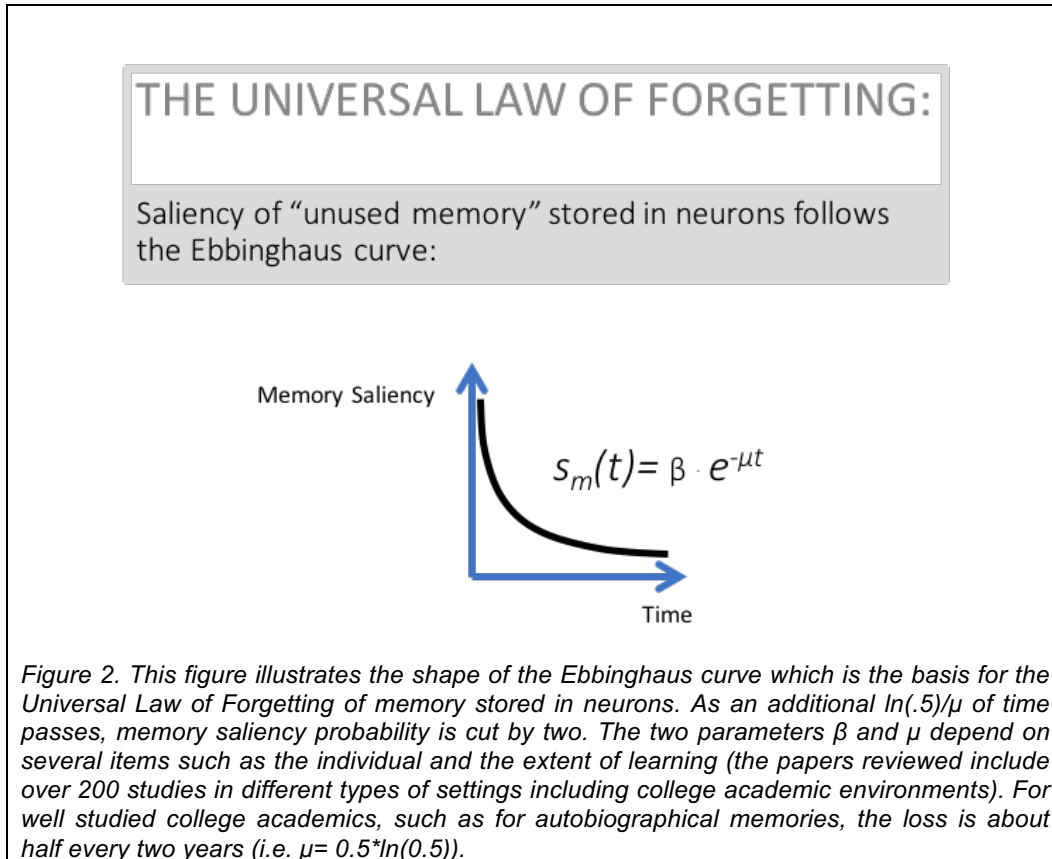
Rubin and Wenzel [7] analyze 210 data sets from research spanning one century and find not a single one spanning more than a year in the field of education. There is a group of papers that analyzes biographical memory which focusses in periods up to 20 years long. Rubin and Wenzel analyze various types of curves finding four of them match equally well all data sets less than a year old and report the longer memory loss ones (several years) require a slightly different kind of curve. This is relevant for our research for two reasons: first, based on their search there are no papers on academic memory loss that expand beyond one year (except a handful such as Bahrick’s research on language education that we will review latter in the paper) and second, the longer term memory optimally fitting curve may be slightly different than the short term one but with a curve that is essentially of the same type. In fact, they explicitly indicate their results can not rule out the conjecture that the underlying curves are exactly the same. Murre and Dros [8] have also tested various formulas to replicate the Ebbinghaus curve over a period of one month finding even more consistency with our main claim. Using on-line software [9] retention findings on language acquisition are consistent with forgetting curve up to a year, at least, with a sample of over 125.000 students. The noise in their results suggests there are many factors that influence retention as we will see in the next sections.

Rubin and Wenzel’s conclusion that short-term learning decay can be modeled by a given universal function is consistent with the overwhelming evidence that forgetting is unavoidable and fairly independent of anything other than initial learning. Neither population aspects (such as age, intoxicated levels or amnesia conditions [10, 11, 12]), learning process [13, 14], nature of the task (e.g. autobiographical memory [15, 16], meaningfulness and difficulty [13]), dependent variable (% correct, d' , $\log d$, ebb, $p/(1-p)$, odds ratio [7]) nor test procedures (recall versus recognition [17, 18]) have been shown to alter the forgetting process. Rubin and Wenzel [7] also review 37 experiments showing animal memory also behaves similarly. Yin et al [19], in experiments with *Drosophila* show the effects of CREB in long-term memory [20]. In fact, like in humans, mass-practice without rest-periods in *Drosophila* seem to prevent long-term learning and lack of practice (or re-learning) results in no memory at all. As Tsai [21] first pointed out, unless there is relearning, forgetting seems to exhibit a decay curve that depends only on initial learning (the similarities between humans and *Drosophila* in this regard illustrate just how brutal nature is about forgetting everything that is not used).

3.3 Autobiography

Autobiographical memory of college is most likely forgotten also at “Ebbinghaus Speed”, and perhaps at exactly the same rate since there are no experiments found (so far) showing a different behavior between the two. College is often linked to some major changes in personal life providing a good ground for testing forgetting of unused memories (and a possible comparison with academic content). Unfortunately, we have found no research comparing the decay of autobiographical memory with that of college academics, however, existing research on autobiographical memory also confirms an exponential type retention function [16]. Existing research extends this hypothesis beyond the simple

effect of time and show other factors determining overall remembering behavior [22, 23, 24] such as a performance increase the more cues given, but still, even with cues, forgetting occurs at Ebbinghaus speed (albeit slower than without cues). Similar results were found by Reiser et al [25]. This connection may also explain other aspects such as inaccuracies and overconfidence of personal recall [26], even to the extent of lowering accuracy below guess levels [27]. Burrell et al [28] showed emotional stimulus greatly increase retention (while unemotional stimulus brings no salient retention). Nickerson and Adams [29] demonstrated that even everyday objects are not well remembered and argue that only “useful” information is memorized. In other words, we only store what we really need. Autobiographical memory seems to have a role in how we view ourselves and the distribution of memories over a lifespan (for adults 70+) depends on psychosocial preferences and culture but exhibits an overall n-shape retrieval curve [30].



Accuracy of autobiographical memories has been addressed by various experiments showing unintuitive results [31]. Loftus and Palmer [32] demonstrated the choice of question influences memory interpretations (“smashed into” versus “touched each other” yields significantly different estimates for collision speed given the same collision’s video with differences of over 30%) – an aspect which is of major concern in legal procedures. In history, memory is not only forgotten but distorted [33]. Hirst et al [34] in a 10-year experiment found rapid event memory forgetting occurred during the first year and then leveled off soon after that. Inaccurate memories were formed during the first year and persisted in time (unless persistently corrected by outside forces). More worrisome, we tend to believe we know things better than we really do.

3.4 Permastore and second language acquisition

Bahrck [35] performed a longitudinal research which attempted to demonstrate that some language learned at school can be retained for long periods of time. The possibility of a constant term is also discussed by Wixted [36] in the context of reviewing work on Jost’s law of forgetting [37] and Ribot’s law of retrograde amnesia [38]. The research hypothesis was that forgetting stops after a number of

years once knowledge has been “solidified” and hence the notion of “permastore”. Bahrick pioneered a methodology that could well be used in other subject domains. Unfortunately, at this point it is unclear whether and how the findings may extend to other domains and the research has not been replicated. In contrast, Hintzman [39] provides evidence that what’s behind Bahrick’s findings is simply grade inflation, and not any permanent memory recall. The domain of language may also prove a tricky one for two additional reasons, first, Spanish is the second language in the US leaving the door to some possible re-use as part of the daily life of subjects, and second, we have some innate language abilities that may confound the results.

3.5 The retention of “Hard” knowledge like STEM subjects

Many of the subjects in STEM are never used after the final exam, are difficult to master, and arguably completely unrelated to innate abilities, making them ideal to test the hypothesis that unused college academics is forgotten at “Ebbinghaus speed”. Again, all research evidence is consistent with our hypothesis. However, findings of the analysis of this review show that, despite the rapidly growing number of publications in the field, practically all of them study memory retention by researching the retention of learning of elements unrelated to sophisticated STEM concepts; such as syllables, series of words, words in a foreign language, personal experiences, number series, emotional memories. The number of studies that explored memory retention by studying STEM related content appeared to be extremely few and leave many doors unexplored [40].

About 50% of what is learned in a Mechanics freshman class is lost by the senior year [1] unless it is re-used, in which case performance may even improve. The research is inconclusive as to the reasons for such improvement nor gives any hints as to how to increase (or measure) retention. Sayre et al [41] also show that retention and mastery are correlated with practice but again, in a short-term analysis and without any hints for improvement. The literature referenced in both papers suggests a lack of careful analysis of the important topics covered in both these papers. Strategies for re-learning may vastly improve retention and should be further researched. Direnga et al [42] showed that members active in the subject show improvements which may mean that Ebbinghaus speed does not apply 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.

Some work exists in retention of STEM education at the high-school level which may be relevant to College Academics. Grundmeyer [44] found two months and a half after taking tests, A level high-school students score 25% lower on the same tests (imagine what would happen after two years) and B and C students scored 35% lower than their original scores. This suggests undergraduates are better (since they lose about 30% the first year and 50% in two years [40]) and is possible that certain subjects exhibit longer term retention than others – independently of the shape of the forgetting curve. By raising initial learning, college educators may delay memory decay but not necessarily impede it – without additional research, they do so blinded to what learnings move to long-term memory and how to approach lifelong learning (and re-learning when necessary).

Custers and ten Cate [45] suggest that very little knowledge is lost after 1 or 2 years after it has been used but then it follows a forgetting curve and about 15-20% is retained 25 years later. However, this research has not been replicated and is based on basic science which opens the door for the same issues discussed on our permastore discussion above (most notably Hintzman’s grade inflation hypothesis and the potential re-use/re-fresh of basic science). It’s hard to imagine basic science concepts are not reviewed in the daily life of a medical doctor, suggesting they test retention of used material (not of unused material as we are interested in here).

3.6 Vision and other “naturally” long-term retention skills

Is there a stock of memories that humans retain long-term? Walking? Faces? If not, what is the stock of functions that humans naturally “re-fresh”? Is there a cultural imprint set at youth that remains imprinted over time regardless of future living conditions? If the answer to any of these is no, how can we explain “pre-wired” skills? Aren’t this remembered long-term? The boundary between the two is a subject we feel should deserve further attention. We have not seen any significant connection in the literature between any of the “naturally” long-term skills and what students remember years after graduation. There are indeed domains where there seems to be long-term learning effects like stereoscopic vision or even face recognition, which exhibits special long-term retention [46], seems to be hardwired from birth [47] and may have all together a different mechanism [48] with age-specific after effects [49]. There exists a lot of research about newborn visual perception mechanisms [50] that

seems to develop in the last weeks of pregnancy [51]. In any case, accuracy perception seems to be impaired [52] suggesting limited cognitive reasoning. There does not seem to be any links between face recognition and regular learning other than perhaps as an anchor in which to build learning memories. Similar mechanisms may exist for more general image memorization [53]. For example, in cats, some basic visual skills, such as perceiving vertical lines, can only be learned and retained if practiced in the first three months of life [54]. In fact, 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). Face recognition seems to follow also the Ebbinghaus curve [60] even when one can expect some degree of transferability or reinforcement (but even unused childhood languages are forgotten...). Image recognition seems to be very common and abstract in birds [55, 56] while math is not [57]. In non-human mammals, there is evidence that some various mathematical abilities are possible, to an extent somewhat controversial in the literature [58] which raises doubts as to whether basic mathematical skills that seem retained many years beyond graduation are simply a basic elaboration of what we can do without formal learning – a conjecture that has not yet been researched based on our survey. Support for this conjecture can also be found in infants, since they can discriminate between 2 and 3 objects in their first week of life [59] and 6 to 12 objects when they are only six-month-old, long before the emergence of language [60], suggesting sophisticated pre-wired mathematical abilities in humans. The body of research that the papers referenced in this paragraph are part of, has been largely ignored by the pedagogical literature that we have reviewed (despite striking similarities between the forgetting curve in humans and in animals [7]). That over fifty years have passed since the publishing of Herstein's [55] research without an impact in pedagogy gives a glimpse of how disconnected communities are.

3.7 Three unaddressed aspects of forgetting

There are three aspects of the long-term forgetting curve that have not been addressed holistically: What do we forget? What are the different variables that influence the rate of forgetting (other than time)? What is the impact on forgetting of various pedagogical approaches? We now briefly review these three questions in turn.

3.7.1 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. Ellis et al [63] make the case that A level students and tutors remember content better the first years which is consistent with mastery impacting retention. Once a mastery threshold is lost, all students may retain the same amount. A related issue largely unaddressed in the literature is what collective knowledge (not individual) is forgotten. Argote et al [64], show evidence of how knowledge learned in an in-the-job setting is rapidly forgotten, with over 72% of knowledge being forgotten the first year.

3.7.2 What are the different variables that influence the rate of forgetting (other than time)?

On the second question, the forgetting curve may be shaped by factors that have not been reviewed in the literature, perhaps not even addressed or ever suggested including a more complex set of values (e.g. affection and social interaction [65]), memory flaws [66], type of memory [67, 68]. Wixted [69] suggests that perhaps there is a different behavior between memories that have not consolidated and those that have. Another related aspect that has not been addressed is when is memory "refreshed" or "practiced", in other words, when should we re-set 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?

3.7.3 What is the impact on long-term forgetting of various pedagogical approaches?

Finally on the third question, there seems to be a disconnect between learning science methods and long-term retention. Among all perused, too many to cite, all papers measuring performance improvements do so in the short term. These include papers on scheduling (massed practice, variation, retrieval learning, spaced retrieval, segment learning, interleaved learning), content presented (germane cognitive load, clean content organization, present with context, advance organizers, goldilocks' principle, embodied cognition), medium used (audio or graphics, graphics and text, audio and text, clean, drawing by hand over CAD, social context, projects, tutorials, hand-drawing, student learning), role of testing (pick the right assessments, worked examples, unsolved problems for experts, elaboration, reflection, depth & breadth discovery), feedback (Delayed feedback, cognitive feedback, cognitive tutors) and pre-conditions (Pretesting, curiosity matters, grit, intent makes a difference). Metzler-Baddeley et al. [70] conducted an experiment that illustrates a possible way to test retention effects. They compared adaptive and non-adaptive training with mix results. They found adaptive learning has some advantages over non-adaptive learning but recognize the effect is small and that it is unclear if it is adaptive spacing or repetition that has the bigger effect. Learning engineering will certainly develop ways to track long-term retention, but not to date.

- **Pre-learning:** Pretesting, curiosity matter, Intent makes a difference
- **Content:** Germane cognitive load, present with context, advance organizers, goldilocks' principle, embodied cognition
- **Medium:** Audio or graphics, clean, drawing, social context, projects, tutorials, hand-drawing, student learning
- **Practicing:** Massed Practice, variation, retrieval learning, spaced retrieval, segment learning, interleaved learning
- **Testing:** Pick the right assessments, worked examples, unsolved problems for experts, elaboration, reflection, depth & breadth discovery
- **Feedback:** Delayed feedback, cognitive feedback

Figure 3. This figure illustrates various learning practices that have been reviewed, without finding any evidence of a long-term retention experiment that links performance with a given practice. The methodologies have been organized using a novel taxonomy based on time of use within the learning cycle.

4 CONCLUSIONS

We have not found any research evidence that unused academic content is retained long-term – all the literature surveyed is consistent with an “Ebbinghaus forgetting law” that is universal across the animal kingdom. Forgetting seems to be a very fundamental process in the brain (*we are constantly forgetting at Ebbinghaus speed*) that has been shown at the cell level and in many other species. We have not yet identified any paper supporting the conventional wisdom claiming that what you learn in college and retain long-term is “how to think” or some “metacognition skill”. No paper seems to look at whether there is a correlation between type of memory and retention rates. However, the number of papers addressing directly long-term retention is very small and many issues remain to be researched as was discussed in the previous section. If forgetting follows the Ebbinghaus curve, how can we measure the strength of a memory in a way that can help us predict it's future forgetting and optimal subsequent practice? No research was found on the most effective practice schedule to predict forgetting, nor to insure long-term retention of a subject. More worrisome, the work on long-term autobiographical memory suggests humans distort memories at a very rapid and broad pace, while

remaining falsely confident of their retention rates suggesting that academic content, and associated confidence, may also be distorted as time goes by.

This does not mean that going to college is of questionable value nor that all content is forgotten. We remain strong believers in the greater value of college education and there are numerous pieces of evidence suggesting there is. The brain may behave a bit like regular physical muscles and practice may increase their ability to absorb new material as shown with the growth of cortex in learners or even taxi drivers [71, 72, 73]. Going through the hurdles of a college education may signal grit or even further develop it. The head start on the establishment of a professional network may also be behind the value of a college education. The field of economics, although disconnected from memory retention research, has produced a lot of results on the value of a college degree. We do not intend to review in detail this body of research because it is beyond the scope of this paper and because we have not found a single paper that connect economics and memory retention, which, again, should provide some hints as to what is it the role of memory retention in college graduation value. Research shows that subject grades are a good predictor of academic success. For example, high-school grades seem to be a good predictor of college success [74], but grades don't seem to be a good predictor of professional success. The literature on economics seems to distinguish a "signaling value" for BA graduates that has only two levels, or two curves of success, BA graduation and ivy league graduation [75, 76, 77]. A proper technology for researching forgetting may have an impact in policy decisions, for example, in choosing between accelerated and non-accelerated formats (e.g. [78]).

Our review has prompted a number of other conjectures and open issues consistent with the papers reviewed which we feel deserve future research. If it's true that long-term retention is only achievable through subsequent use, we should aim to target academic content at building expertise – but what is expertise in a field? Should the four-year college model be re-designed into a part-time longer period so that more practice can be built over a long-period to ensure better learning? Is the forgetting domain-specific?

Our review is consistent with some practical advice that requires further research. 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. 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.

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: 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. 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. 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.

REFERENCES

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- [1] Barrantes, Analia, Andrew Paul, and David E. Pritchard 2009. "What Do Seniors Remember from Freshman Physics?". AIP Conf. Proc 1179 (2009): 47–50.
- [2] Ramón y Cajal, S. (1881). Observaciones microscópicas sobre las terminaciones nerviosas en los musculos voluntarios de la rana. *Zaragoza*, 644.
- [3] Ebbinghaus H (1880) Urmanuskript "Ueber das Gedächtniß". Passau: Passavia Universitätsverlag.
- [4] Jost, A. (1897). Die Assoziationsfestigkeit in ihrer Abhängigkeit von der Verteilung der Wiederholungen [The strength of associations in their dependence on the distribution of repetitions]. *Zeitschrift für Psychologie und Physiologie der Sinnesorgane*, 16, 436–472.
- [5] Ribot, T. (1881). *The diseases of memory: An essay in the positive psychology* (W. H. Smith, Trans.). London: Kegan Paul, Trench, & Co.
- [6] Subirana, Brian, Aikaterini Bagiati and Sanjay. E. Sarma (2017). "On College Academics Forgetting: At "Ebbinghaus Speed". To appear in: *Edulearn 2017 Conf. Proceedings*
- [7] Rubin, D.C. and Wenzel, A.E., 1996. One hundred years of forgetting: A quantitative description of retention. *Psychological review*, 103(4), p.734.
- [8] Murre, J.M. and Dros, J., 2015. Replication and analysis of Ebbinghaus' forgetting curve. *PLoS one*, 10(7), p.e0120644.
- [9] Ridgeway, K., Mozer, M.C., Bowles, A. and Stone, R., 2016. Forgetting of foreign-language skills: A corpus-based analysis of online tutoring software. *Cognitive Science Journal*.
- [10] Wickelgren, W. A. (1968). Sparing of short-term memory in an amnesic patient: Implications of strength theory of memory. *Neuropsychologia*, 6, pp 235-244.
- [11] Wickelgren, W. A. (1975a). Age and storage dynamics in continuous recognition memory. *Developmental Psychology*, 11, pp 165-169.
- [12] Wickelgren, W. A. (1975b). Alcoholic intoxication and memory storage dynamics. *Memory & Cognition*, 3, pp 385-389.
- [13] Underwood (1962), B.J. *Experimental psychology*. NY: Appleton-Century-Crofts, 1966. 2nd ed.
- [14] Nelson, T. O., & Vining, S. K. (1978). Effect of semantic versus structural processing on long-term retention. *Journal of Experimental Psychology: Human Learning and Memory*, 4(3), 198.
- [15] Galton, F. (1879) Psychometric experiments. *Brain* 2, pp 148-162
- [16] Rubin, D.C., 1982. On the retention function for autobiographical memory. *Journal of Verbal Learning and Verbal Behavior*, 21(1), pp.21-38.
- [17] Burn, H. E., & Dobell, E. M. (1925). The curve of forgetting for advertising material. *JAP*, 9, pp 5-21.
- [18] Luh, C. W. (1922). The conditions of retention. *Psychological Monographs*, 31, whole no. 142.
- [19] Yin, J.C.P., Del Vecchio, M., Zhou, H. and Tully, T., 1995. CREB as a memory modulator: induced expression of a dCREB2 activator isoform enhances long-term memory in Drosophila. *Cell*, 81(1), pp.107-115.
- [20] Silva, A.J., Kogan, J.H., Frankland, P.W. and Kida, S., 1998. CREB and memory. *Annual review of neuroscience*, 21(1), pp.127-148.
- [21] Tsai, C. (1924). A comparative study of retention curves for motor habits. *Comparative Psychology Monographs*, 2, pp 1-29
- [22] Cabeza, R. and St Jacques, P., 2007. Functional neuroimaging of autobiographical memory. *Trends in cognitive sciences*, 11(5), pp.219-227.
- [23] Robinson, J. A. (1976). Sampling autobiographical memory. *Cognitive psychology*, 8(4), 578-595.
- [24] Wagenaar, W. A. (1986). My memory: A study of autobiographical memory over six years. *Cognitive psychology*, 18(2), 225-252.
- [25] Reiser, B. J., Black, J. B., & Abelson, R. P. (1985). Knowledge structures in the organization and retrieval of autobiographical memories. *Cognitive psychology*, 17(1), 89-137.
- [26] Barclay, C.R. and Wellman, H.M., 1986. Accuracies and inaccuracies in autobiographical memories. *Journal of Memory and Language*, 25(1), pp.93-103.
- [27] Wagenaar, W. A. (1988). Calibration and the effects of knowledge and reconstruction in retrieval from memory. *Cognition*, 28(3), 277-296.
- [28] Burrell, L.V., Johnson, M.S. and Melinder, A., 2016. Children as Earwitnesses: Memory for Emotional Auditory Events. *Applied Cognitive Psychology*.

-
- [29] Nickerson, R.S. and Adams, M.J., 1979. Long-term memory for a common object. *Cognitive Psychology*, 11(3), pp.287-307.
- [30] Conway, M.A., 2005. Memory and the self. *Journal of memory and language*, 53(4), pp.594-628.
- [31] Goldsmith, M., Koriat, A. and Pansky, A., 2005. Strategic regulation of grain size in memory reporting over time. *Journal of Memory and Language*, 52(4), pp.505-525.
- [32] Loftus, E.F. and Palmer, J.C., 1996. Eyewitness testimony. In *Introducing Psychological Research* (pp. 305-309). Macmillan Education UK
- [33] Thelen, D., 1989. Memory and American history. *The Journal of American History*, 75(4), pp.1117-1129.
- [34] Hirst, W., Phelps, E.A., Meksin, R., Vaidya, C.J., Johnson, M.K., Mitchell, K.J., Buckner, R.L., Budson, A.E., Gabrieli, J.D., Lustig, C. and Mather, M., 2015. A ten-year follow-up of a study of memory for the attack of September 11, 2001: Flashbulb memories and memories for flashbulb events. *Journal of Experimental Psychology: General*, 144(3), p.604.
- [35] Bahrack, H.P., 1984. Semantic memory content in permastore: fifty years of memory for Spanish learned in school. *Journal of experimental psychology: General*, 113(1), p.1.
- [36] Wixted, J. T. (2004). On Common Ground: Jost's (1897) Law of Forgetting and Ribot's (1881) Law of Retrograde Amnesia. *Psychological Review*, Vol 111(4), Oct 2004, 864-879
- [37] Jost, A. (1897). Die Assoziationsfestigkeit in ihrer Abhängigkeit von der Verteilung der Wiederholungen [The strength of associations in their dependence on the distribution of repetitions]. *Zeitschrift für Psychologie und Physiologie der Sinnesorgane*, 16, 436-472.
- [38] Ribot, T. (1881). *The diseases of memory: An essay in the positive psychology* (W. H. Smith, Trans.). London: Kegan Paul, Trench, & Co.
- [39] Hintzman, D. (1990). Permastore or grade inflation? Adjusting Bahrack's data for changes in academic standards (No. 90-15). Tech. Rep.
- [40] Custers, E.J., 2010. Long-term retention of basic science knowledge: a review study. *Advances in Health Sciences Education*, 15(1), pp.109-128.
- [41] Sayre, E.C., Franklin, S.V., Dymek, S., Clark, J. and Sun, Y., 2012. Learning, retention, and forgetting of Newton's third law throughout university physics. *Physical Review Special Topics-Physics Education Research*, 8(1), 010116 pp1-10
- [42] Direnga, J., Presentati, M. B., Timmermann, M. D., Brose, A., & Kautz, C. H. (2015). Does it stick?-Investigating long-term retention of conceptual knowledge in mechanics instruction. *Age*, 26, 1.
- [43] Fritz, D., Hu, A., Wilson, T., Ladak, H., Haase, P. and Fung, K., 2011. Long-term retention of a 3-dimensional educational computer model of the larynx: a follow-up study. *Archives of Otolaryngology-Head & Neck Surgery*, 137(6), pp.598-603.
- [44] Grundmeyer, T., 2015. How Much Content Do High School Students Retain? *American Secondary Education*, 44(1), p.62.
- [45] Custers, E.J. and ten Cate, O.T., 2011. Very long-term retention of basic science knowledge in doctors after graduation. *Medical education*, 45(4), pp.422-430.
- [46] Bahrack, H.P., Bahrack, P.O. and Wittlinger, R.P., 1975. Fifty years of memory for names and faces: A cross-sectional approach. *Journal of experimental psychology: General*, 104(1), p.54.
- [47] De Haan, M., Pascalis, O. and Johnson, M.H., 2002. Specialization of neural mechanisms underlying face recognition in human infants. *Journal of cognitive neuroscience*, 14(2), pp.199-209.
- [48] Tanaka, J.W. and Simonyi, D., 2016. The "parts and wholes" of face recognition: A review of the literature. *The Quarterly Journal of Experimental Psychology*, pp.1-14.
- [49] Lai, M., Oruç, I. and Barton, J.J., 2012. Facial age after-effects show partial identity invariance and transfer from hands to faces. *Cortex*, 48(4), pp.477-486.
- [50] Goren, C.C., Sarty, M. and Wu, P.Y., 1975. Visual following and pattern discrimination of face-like stimuli by newborn infants. *Pediatrics*, 56(4), pp.544-549.
- [51] Pereira, S.A., Junior, A.P., da Costa, M.F., Monteiro, M.D.V., de Almeida, V.A., da Fonseca Filho, G.G., Arrais, N. And Simion, F., 2016. A comparison between preterm and full-term infants' preference for faces. *Jornal de Pediatria*.
- [52] Bindemann, M., Attard, J. and Johnston, R.A., 2014. Perceived ability and actual recognition accuracy for unfamiliar and famous faces. *Cogent Psychology*, 1(1), p.986903.
- [53] Xue, G., Mei, L., Chen, C., Lu, Z. L., Poldrack, R., & Dong, Q. (2011). Spaced learning enhances subsequent recognition memory by reducing neural repetition suppression. *Journal of cognitive neuroscience*, 23(7), 1624-1633.
- [54] Hubel, D. H., & Wiesel, T. N. (1963). Receptive fields of cells in striate cortex of very young, visually inexperienced kittens. *J. neurophysiol*, 26(994), 1002.

-
- [55] Herrnstein, R.J. and Loveland, D.H., 1964. Complex visual concept in the pigeon. *Science*, 146(3643), pp.549-551.
- [56] Roberts, W.A. and Mazmanian, D.S., 1988. Concept learning at different levels of abstraction by pigeons, monkeys, and people. *Journal of Experimental Psychology: Animal Behavior Processes*, 14(3), p.247.
- [57] Haywood, S., 2016. Can birds count eggs in their nests?. *Ibis*, 158(1), pp.195-198.
- [58] Agrillo, C. and Bisazza, A., 2014. Spontaneous versus trained numerical abilities. A comparison between the two main tools to study numerical competence in non-human animals. *Journal of neuroscience methods*, 234, pp.82-91.
- [59] Antell, S.E. and Keating, D.P., 1983. Perception of numerical invariance in neonates. *Child development*, pp.695-701.
- [60] Xu, F. and Spelke, E.S., 2000. Large number discrimination in 6-month-old infants. *Cognition*, 74(1), pp.B1-B11.
- [61] Bloom, B. S.; Engelhart, M. D.; Furst, E. J.; Hill, W. H.; Krathwohl, D. R. (1956). *Taxonomy of educational objectives: The classification of educational goals*. Handbook I: Cognitive domain. New York: David McKay Company.
- [62] Richardson-Klavehn, A. and Bjork, R.A., 1988. Measures of memory. *Annual review of psychology*, 39(1), pp.475-543.
- [63] Ellis, J.A., Semb, G.B. and Cole, B., 1998. Very long-term memory for information taught in school. *Contemporary educational psychology*, 23(4), pp.419-433.
- [64] Argote, L., Beckman, S.L. and Epple, D., 1990. The persistence and transfer of learning in industrial settings. *Management science*, 36(2), pp.140-154.
- [65] Picard, R.W., Papert, S., Bender, W., Blumberg, B., Breazeal, C., Cavallo, D., Machover, T., Resnick, M., Roy, D. and Strohecker, C., 2004. Affective learning—a manifesto. *BT technology journal*, 22(4), pp.253-269.
- [66] Schacter, D.L., 2002. The seven sins of memory: How the mind forgets and remembers. Houghton Mifflin Harcourt.
- [67] Sadeh, T., Ozubko, J.D., Winocur, G. and Moscovitch, M., 2016. Forgetting Patterns Differentiate Between Two Forms of Memory Representation. *Psychological science*, 27(6), pp.810-820.
- [68] Weimer-Stuckmann, G., 2009. *Second Language Vocabulary Acquisition: Spacing and Frequency of Rehearsals* (Master's dissertation, University of Victoria).
- [69] Wixted, J.T., 2005. A theory about why we forget what we once knew. *Current Directions in Psychological Science*, 14(1), pp.6-9.
- [70] Metzler- Baddeley, C. and Baddeley, R.J., 2009. Does adaptive training work? *Applied Cognitive Psychology*, 23(2), pp.254-266.
- [71] Thompson, T. W., Waskom, M. L., & Gabrieli, J. D. (2016). Intensive working memory training produces functional changes in large-scale frontoparietal networks. *Journal of cognitive neuroscience*.
- [72] Yoo, J. J., Hinds, O., Ofen, N., Thompson, T. W., Whitfield-Gabrieli, S., Triantafyllou, C., & Gabrieli, J. D. (2012). When the brain is prepared to learn: enhancing human learning using real-time fMRI. *NeuroImage*, 59(1), 846-852.
- [73] Maguire, E. A., Gadian, D. G., Johnsrude, I. S., Good, C. D., Ashburner, J., Frackowiak, R. S., & Frith, C. D. (2000). Navigation-related structural change in the hippocampi of taxi drivers. *Proceedings of the National Academy of Sciences*, 97(8), 4398-4403.
- [74] Geiser, S. and Santelices, M.V., 2007. Validity of High-School Grades in Predicting Student Success beyond the Freshman Year: High-School Record vs. Standardized Tests as Indicators of Four-Year College Outcomes. Research & Occasional Paper Series: CSHE. 6.07. *Center for studies in higher education*.
- [75] Grubb, W.N., 1993. The varied economic returns to postsecondary education: New evidence from the class of 1972. *Journal of Human resources*, pp.365-382.
- [76] Autor, D. H., Katz, L. F., & Kearney, M. S. (2008). Trends in US wage inequality: Revising the revisionists. *The Review of economics and statistics*, 90(2), 300-323.
- [77] Avery, C., & Turner, S. (2012). Student loans: Do college students borrow too much—or not enough?. *The Journal of Economic Perspectives*, 26(1), 165-192.
- [78] Faght, B.E., Law, M. and Zahradnik, M., 2016. How Much Do Students Remember Over Time? Longitudinal Knowledge Retention in Traditional versus Accelerated Learning Environments. *Toronto: Higher Education Quality Council of Ontario*.