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ADAPTIVE MEMORY

Novel Findings Acquired Through Forward Engineering

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Scholars of memory know a lot about how human memory works. Remembering is largely reconstructive, for example, and spaced practice leads to longer-lasting retention than massed practice. Experiments have shown that immediate memory span is sharply limited, forgetting is a negatively accelerated function of time, and items near the beginning and end of a list are remembered best. Each of these empirical patterns is well-established, forming core phenomena of general memory textbooks, but little is known about why our memory systems actually work this way.

As an exercise, try constructing a memory system from scratch. Would you build-in negatively accelerated forgetting, or an advantage for spaced practice? Could you justify why your system is fundamentally reconstructive? Does it make sense to have a retention system that is more sensitive to pictures than to words, or one that is biased toward retaining items that occur early in a sequence? Most memory researchers would have trouble answering these questions, primarily because researchers rarely consider the function of memory in their analyses. The particular problems that our retention systems are built to solve, which presumably shape their operating characteristics, remain largely unknown.

This chapter is divided into three main sections. In the first, I consider why functional questions are often ignored by the community of memory researchers. The reason is partly that our standard research methodology—reverse engineering—relegates functional analyses to the status of a "just-so" story, a form of post-hoc speculation that is anathema to most researchers. Second, I consider an alternative approach—forward engineering—in which functional considerations play the primary role. Rather than attempting to reverse engineer an empirical phenomenon, such as the serial position curve, forward engineering takes a design stance. It starts with an analysis of recurrent problems posed by the environment, such as remembering the location of food, and attempts to infer the features of a viable "solution." Possible internal mechanisms are proposed, and the research strategy is then to investigate whether the proposed mechanisms might actually exist. I end the chapter by briefly reviewing some recent research from our laboratory that shows the value of adopting such an approach.

The Standard Method: Reverse Engineering

If the goal is to understand memory, then it seems sensible to begin by investigating how people remember and forget. This was the strategy adopted by Ebbinghaus (1885), who originally brought the investigation of retention under experimental control. Our capacity to remember can be queried, in Ebbinghaus' case by memorizing and recalling ordered sequences of information, and performance systematically recorded and analyzed. Viewed in this way, memory represents a "black box," something that can be broken down and analyzed through rigorous empirical investigation. The core phenomena listed earlier were discovered largely through the application of the Ebbinghaus strategy.

This method is known more generally as *reverse engineering*. When a competitor introduces a new device onto the market, product engineers pick it apart and analyze its structure in order to see how it works. They examine its component parts, noting how they interact, and stress the device to determine its performance limits. The goal is to replicate the device and, ultimately, to improve its efficiency. In the case of the human mind, cognitive scientists seek to reverse engineer cognitive systems—e.g., for memory, they test the limits and scope of remembering to determine how retention systems work.

But there is an important difference. In the case of the product engineer, the function of the device is usually known or obvious—engineers know what the device is designed to do. This is critical because engineers recognize that there is a close relationship between structure and function. The structural features of the device—its "nuts and bolts"—are a byproduct of its functional design. Products are built to perform specific tasks and, for the most part, they don't include structural components that are irrelevant to meeting the desired goal. For this reason, it is difficult to reverse engineer a product without some knowledge of its function. You can query the device—get it to "behave"—but there is no obvious way of determining what the observed behavior means, or even if it is relevant to the system's design.

To illustrate the problem, Klein, Cosmides, Tooby, and Chance (2002) use the example of a three-hole punch. A three-hole punch is designed to punch holes in paper, but imagine trying to reverse engineer the device without knowledge of its function. You could measure its behavior, such as the tension of the springs, but it would be difficult to determine the merit of any given observation. You might find that paper confetti falls out when you shake the device. Would it be worthwhile to concoct a model of confetti formation, or to investigate the boundary conditions for when and how confetti becomes wedged inside the device? Confetti formation is a useless byproduct of punching holes—the true function of the device—but there is no way to gauge the importance of this "behavior" without some prior knowledge of function.

As proxies for function, cognitive researchers typically rely on empirical phenomena. It is the empirical regularity, such as the spacing effect, that serves as the target of investigation. Cognitive researchers ask: What kind of memory system would produce better retention for repetitions that are spaced in time? Solutions are proposed—e.g., items are encoded with respect to changing contexts, spaced repetitions lead to recursive remindings of earlier encounters, and so on—but function plays little or no role in the analysis. As a result, for the reasons discussed above, the diagnostic value of the contribution remains unclear. Is the spacing effect really a central operating characteristic of memory, something that is essential to solving the problems that memory evolved to solve? Or, is it a byproduct of some other design feature more central to memory's ultimate function?[1]

There is an additional concern as well. When the analysis revolves entirely around the empirical phenomenon, then any consideration of function becomes essentially post-hoc. We could speculate about why nature built a memory system that produces the spacing effect, but it would amount to a "just-so" story, a fanciful explanation without a firm empirical grounding (Gould & Lewontin, 1979). One could follow up such speculations with further empirical tests, ones based on hypotheses generated by the functional analysis, but this course of action is rarely taken. Researchers are generally satisfied with explaining the empirical effect itself.

An Alternative: Forward Engineering

It is possible to approach the study of cognitive processes in a different way, by turning the focus away from empirical phenomena toward the study of environmental demands. Rather than asking about the components that are needed to explain an empirical pattern, one shifts the explanatory burden to the environment. What are the environmental problems that our memory systems need to solve? What kinds of processes are necessary to solve these problems? Notice that in this case, a strategy known as forward engineering, functional questions take the driving role. The empirical task then becomes one of discovering the proximate machinery that is needed for the system to reach the desired end (see Bruce, 1985).

Both forward and reverse engineering share the same goal—understanding the structure and design of cognitive systems—and both can be used effectively to achieve that goal. But whereas reverse engineering is often functionally rudderless, forward engineering accepts the intimate relationship between function and design. Just as the organs of the body are designed to accomplish specific ends, such as pumping or filtering blood, cognitive systems are assumed to share similar problem-based specificity. Rather than a general-purpose storage system, our capacity to remember exists in order for us to achieve certain specific adaptive ends.[2]

The critical question then becomes one of determining the set of problems that our cognitive systems are attempting to solve. In some areas of cognition, particularly the study of perceptual processes, many of the problems are clear. Everyone agrees, for example, that the visual system is designed in part to solve specific problems—e.g., transducing electromagnetic energy into the electrochemical language of the brain, maintaining constancy in shape and size, determining the depth of objects in space, and so on. But in the case of memory, the problems to be solved are not obvious.

Decades ago, Ulric Neisser championed a form of forward engineering based on the study of remembering as it operates in natural settings. Here the emphasis was placed on real-world problems, such as remembering to take medication, rather than on performance in traditional laboratory tasks (see Neisser, 1978). The aptly named "everyday memory" movement broadened the range of topics addressed by researchers, but remained controversial. Simply adopting a "real-world" criterion provides little guidance on the importance of a problem, at least from a design standpoint, for the same reasons outlined in the three-hole punch example. Critics also raised questions about the generalizability of research on everyday memory problems, as well as the extent to which experimental rigor could be applied to these situations (Banaji & Crowder, 1989).

The advent of evolutionary psychology, however, provides us with a more principled way to proceed. Human memory clearly evolved and nature brings its own criteria to the shaping of a cognitive system. Nature's main criterion, as embodied through the process of natural selection, is the enhancement of inclusive fitness (e.g., Williams, 1966). At some point in our ancestral past, memory systems developed because they helped solve problems related to survival and reproduction. Inclusive fitness is the engine driving natural selection, so it is reasonable to assume that the "purpose" of memory, at least from an evolutionary perspective, was to help us survive long enough to reproduce or to secure an acceptable mating partner. An organism with the capacity to remember the location of food, or categories of potential predators, is more likely to survive than an organism lacking this capacity.

Our retention systems do appear to act functionally, at least in tracking the way events occur and recur naturally in the environment. Forgetting functions are generally negatively accelerated, which means that most forgetting occurs early after event exposure and slows thereafter. Anderson and Schooler (1991) have shown that everyday event repetitions share similar statistical properties. For example, if the word "sequester" appears in the headlines of the *New York Times* today, there is a good chance that it will appear again tomorrow. However, the odds fall off with each successive day in a form that mimics the classic forgetting function. Anderson and Schooler (1991) argue that "forgetting" is simply an optimal reflection of the way events recur in the environment. We are less likely to remember an event with time because that event is less likely to recur and be needed.

It is important to note, though, that evolutionary theory does not demand that evolved systems function solely in the service of enhancing fitness or optimality. Nature's criterion drives natural selection, but that does not mean that evolved systems will maximize fitness or necessarily work most efficiently when asked to solve the problems that led to their development (Symons, 1992). Yet, focusing on the potential fitness-enhancing properties of an evolved system is a reasonable way to generate hypotheses about its ultimate function. For example, recent research on adaptive memory originated from the claim that our memory systems are functionally specialized to solve adaptive, or fitness-based, problems. I review some of this work in the next section.

Research on Adaptive Memory

For much of the past decade, our laboratory has been investigating whether memory is biased or "tuned" to solve fitness-relevant adaptive problems. Such problems include remembering threats to survival, sources of nourishment, sources of contamination, potential mating partners, cheaters and free-riders, and so on (Nairne & Pandeirada, 2008). The idea that memory is problem-oriented, and specialized to retain certain kinds of information, is a relatively novel idea in the memory field. Most memory researchers assume that memory is controlled by a few domain-general processes, such as elaboration or distinctive processing, that apply equally (at least in principle) to any kind of information content.[3] What matters to remembering are the number of generated retrieval cues, which is determined largely by the richness of the initial encoding, and the extent to which those cues match or are diagnostic of the to-be-remembered information (Roediger & Guynn, 1996; Nairne, 2002).

The adaptive memory movement assumes instead that memory evolved to solve adaptive problems, such as remembering the locations of predators, and that general remembering is largely derivative of these specialized functions. I do not mean to suggest that elaboration or the encoding-retrieval match are unimportant to remembering. The claim is that such processes developed in the service of solving fitness-relevant problems, as proximate mechanisms to achieve adaptive ends. Elaborative processing, for example, may be one of several proximate mechanisms that evolved to ensure excellent retention of fitness-appropriate events (see Kroneisen & Erdfelder, 2011; Nairne, 2014). Our main empirical agenda has been to show that memory functions especially well when encoding tasks tap these adaptive problems.

Survival Processing

Our initial investigation into adaptive memory focused on the mnemonic effects of survival processing. Here the logic was straightforward: Given that memory evolved subject to nature's criterion—the enhancement of fitness—our retention systems might work optimally when information is encoded with respect to its fitness consequences.[4] We chose to focus on survival processing, rather than the inherent content of information (e.g., fitness-relevant stimuli such as food items or predator names), because survival relevance is likely to be context-dependent. A fur coat, for example, is fitness-relevant at the North Pole, but not at most points on the equator.

The survival-processing paradigm was modeled after the classic incidental learning experiments of Hyde and Jenkins (1973) and Craik and Tulving (1975). People were presented with random sets of words which they were required to rate via one of several orienting tasks. In the critical condition, people were asked to imagine being stranded in the grasslands of a foreign land, one in which they would need to find steady supplies of food and water and avoid predators. The task was to rate the relevance of each presented word to this imagined survival scenario. For control comparisons, we included a standard deep-processing task (rating words for pleasantness) along with a matched scenario that was fitness-irrelevant (moving to a foreign land). Later surprise retention tests (free recall and recognition) produced strong retention advantages for items processed with respect to the survival scenario (Nairne, Thompson, & Pandeirada, 2007).

This survival-processing advantage has now been replicated widely, and it is found when compared to a variety of control conditions—even against what are typically thought to be the "best of the best" encoding conditions such as forming a visual image or relating information to the self (Nairne, Pandeirada, & Thompson, 2008). The effect has been demonstrated in small children, in elderly populations, and in populations suffering from mild cognitive impairment (Faria, Pinho, Gonçalves, & Pandeirada, 2009). The effect remains robust in both within- and between-subject designs, in intentional and incidental learning environments, and for both pictures and words. Boundary conditions have been detected, however—for example, survival processing may fail to enhance the retention of stories (Seamon et al., 2012) or faces (Savine, Scullin, & Roediger, 2011), and does not appear on certain implicit memory tests (McBride, Thomas, & Zimmerman, 2013; Tse & Altarriba, 2010).

The fact that survival processing generally produces good retention is consistent with the functional-evolutionary analysis described above. When people are involved in a survival situation—and again, survival processing can presumably be activated in a variety of contexts—processed information is subsequently remembered well. Such a selective tuning for survival-relevant information is almost certainly adaptive. Increasing the availability of fitness-relevant information likely enhances one's ability to survive, a necessary criterion for natural selection. It is therefore reasonable to propose that such a trait gained traction in the population over generations.

Animacy

More recently, our lab has been investigating the mnemonic effects of animacy, defined loosely as the distinction between living and nonliving things. Animacy appears to be a foundational dimension (Opfer & Gelman, 2011). Young children very quickly learn to distinguish between living and nonliving entities. In addition, substantial evidence now exists that animate objects receive priority in attention and visual processing (New, Cosmides, & Tooby, 2007). From an evolutionary standpoint, of course, it makes sense for us to notice and remember living things. Among other things, predators are animate beings, as are prospective mating partners. Yet, despite decades of research on how item characteristics such as word frequency or imageability affect retention, little is known about the mnemonic effects of animacy.

We have explored animacy in two ways. First, we were interested in whether animate words are better remembered than inanimate words, controlling for other item dimensions (e.g., word frequency or concreteness) that could conceivably affect retention (Nairne, VanArsdall, Pandeirada, Cogdill, & LeBreton, 2013). In one study, we carefully matched sets of animate (e.g., turtle) and inanimate words (e.g., purse) along 10 mnemonically relevant dimensions and simply asked people to study and remember the words for a free-recall test. The animate and inanimate words were intermixed in a list and people were given five seconds to study each item. The results of the free recall test are shown in Figure 1.1 for each of three study and test trials. As the figure clearly illustrates, there was a strong recall advantage for the animate items on each of the three trials. In an additional

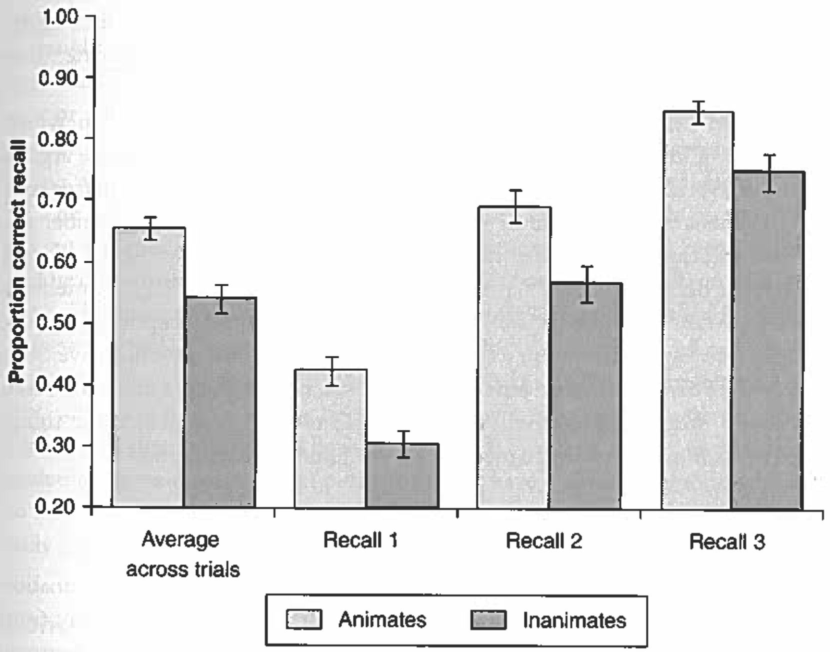

FIGURE 1.1 Proportion correct recall averaged across the three recall trials, and for each recall trial, for animates and inanimates in Experiment 2 of Nairne, VanArsdall, Pandeirada, Cogdill, & LeBreton (2013). Error bars represent standard errors of the mean.

study, we used regression techniques to reanalyze existing recall norms. Rubin and Friendly (1986) investigated predictor variables for 925 nouns but did not include animacy status as a variable. We coded the Rubin and Friendly words for animacy (living versus nonliving) and reanalyzed the data using animacy as an additional predictor variable. Our analysis revealed that animacy was one of the strongest contributors to the explainable variance. Animacy correlated strongly with recall and its incremental importance (the unique contribution of the variable to R^2) was nearly twice that of its nearest competitor, imagery.

We have also explored the mnemonic value of animacy processing (VanArsdall, Nairne, Pandeirada, & Blunt, 2013). Rather than directly comparing the recall of animate and inanimate words, we asked people to process novel stimuli (nonwords) as either living or nonliving things. In these experiments, people were shown pronounceable nonwords (e.g., FRAV) along with properties characteristic of either living (e.g., enjoys cooking) or nonliving (e.g., has a hollow center) things. For each nonword and its assigned property, people were asked to classify the object as a living or nonliving thing. Across participants, every nonword was processed as either a living or a nonliving thing, so the focus could be placed on how the item was processed rather than its inherent item characteristics. Following the classification task, everyone received a memory test for the rated nonwords (free recall or recognition). Once again, there was an animacy advantage—the nonwords classified as animate were recalled and recognized better than those classified as inanimate.

These demonstrated animacy advantages represent another case in which the content of information seems to matter in remembering. As we have argued elsewhere (Nairne & Pandeirada, 2008; Nairne, 2010), from a fitness perspective not all events are created equal—it is much more important to remember the preferred location of a predator than a random twig blowing across the ground (for relevant data see Nairne, VanArsdall, Pandeirada, & Blunt, 2011). A memory system that fails to differentiate between important and unimportant events, defined with respect to nature's criterion of inclusive fitness, would have been unlikely to evolve. Like most other cognitive systems, we need a memory-based "crib sheet," something that will help us attend to and remember those things pertinent to improving the chances of survival and reproduction.

Contamination

Yet another situation in which the content matters is in the risk of contamination from disease. One of the main functions of disgust is to protect the body from contamination via foods, animals, and body parts (e.g., Tybur, Lieberman, Kurzban, & Discoli, 2013). Remembering possible sources of contamination is clearly adaptive, and we were interested in whether contaminated items might be remembered especially well. To investigate this issue, we asked a simple question: Will people remember items that have been touched by a sick person better than items touched by a healthy person? People were shown pictures of everyday objects along with a descriptor signifying the health status of a person who had recently "touched" the object. For example, a picture of a ball was shown along with the statement "person with a constant cough" or the statement "person with a straight nose." After every third item, the three preceding items were shown again and people were required to classify whether each had been touched by a sick or a healthy person. This immediate test was included simply to ensure that people paid attention to the descriptor. After a series of these presentations, everyone was given a surprise free recall test for all of the presented items.

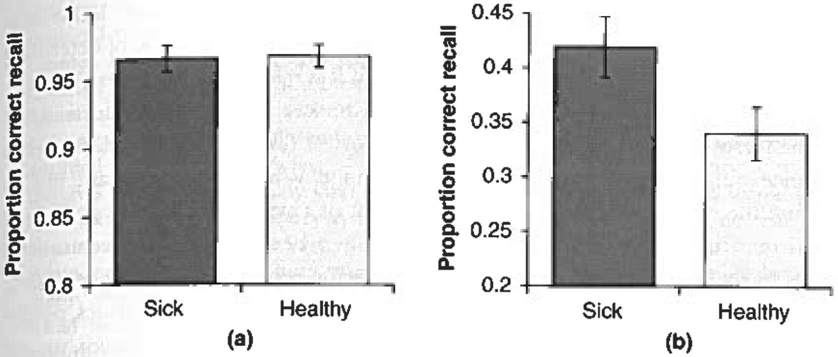

FIGURE 1.2 Proportion correct recall for items that participants had been led to believe had been touched by a sick or a healthy person. Data are shown for both the immediate classification test (a) and for the surprise final free recall test (b). Error bars represent standard errors of the mean.

The data of main interest are shown in Figure 1.2. Performance on the immediate test was excellent, as expected, and no differences were found between the sick and healthy conditions. Again, these tests were designed simply to ensure that people paid attention to the descriptors. Performance on the surprise free recall test, however, revealed a strong recall advantage for the items paired with a "sick" descriptor. Even though people were not expecting a final memory test, those items that were classified as having been touched by a sick person were remembered significantly better than the healthy control. Regardless of the mechanism that underlies the advantage—e.g., perhaps people have a stronger emotional reaction to the contaminated items—the net result is clearly adaptive. Remembering potentially contaminated items can help us to avoid those items in future interactions.

Conclusions

Ever since Ebbinghaus (1885), cognitive researchers have focused their efforts primarily on understanding how memory works. The memory system has been repeatedly queried, by asking people to learn and remember, and lots of empirical regularities have been discovered. Yet, without prior knowledge of the system's function—what memory is designed to do—this kind of reverse engineering has limitations. Empirical regularities might be discovered, but there is no obvious way of determining what the observed behavior means, or even if it is relevant to the system's design.

Given that memory evolved, subject to the constraints of natural selection, we can be reasonably certain about memory's historical function—it was designed to enhance our ability to survive and/or reproduce. While it is important not to confuse the criteria that shape the development of a system with those governing its current functioning, reasonable hypotheses can be generated. For example, it seems likely that memory evolved to solve specific recurrent problems related to survival, such as remembering the location of food, predator characteristics, potential sources of contamination, and so on. Moreover, as with product design, we can assume as well that memory's operating characteristics were specifically shaped to solve problems of this type. This suggests, but does not guarantee, that our capacity to remember and forget should continue to bear the footprint of these original ancestral selection pressures (Nairne et al., 2007). Work in our laboratory on the mnemonic value of survival processing, animacy, and contamination suggests that those footprints are readily detectable in modern memory functioning.

Of course, most of the things we remember are unrelated to fitness, but the fact that people are capable of general remembering does not mean that our memory systems were *designed* (by nature) to remember generally (cf. Nairne, 2014). On the contrary, from an evolutionary perspective content and specificity are likely to play a primary role (see Klein et al., 2002; Nairne, 2010, 2014). But even without the evolutionary focus, and we can never be certain about the adaptive problems that drove the development of cognitive processes (Buller, 2005), functional analyses should be an important component of any researcher's toolkit. As noted at the beginning of the chapter, scholars know a lot about *how* memory works, but little about *why* memory operates as it does. Applying forward functional analysis forces the researcher to consider the why, and recognizes the inherent role that function plays in determining the how (Bruce, 1985). As our recent work on adaptive memory illustrates, adopting such a functional perspective can lead to the discovery of novel empirical phenomena and, perhaps, to a reconsideration of existing phenomena as well.

Notes

1 I am not suggesting that the discovery of the spacing effect, or any of the other empirical phenomena widely studied by memory researchers, has no value. These important discoveries about retention have helped shaped theory and have been used successfully in applied settings. But it remains an open question as to whether these phenomena tell us anything significant about memory's ultimate design and function (although see Anderson & Schooler, 1991).

2 Note that I am using the term "memory" in a very general sense. Although most of the arguments and data presented here apply to episodic memory, our capacity to remember specific episodes, there are undoubtedly multiple memory systems (procedural, semantic, working, etc.). Each presumably evolved to solve its own set of fitness-relevant problems and may possess unique operating characteristics. The study of any memory system, I would argue, can benefit from the kind of functional analysis proposed in this chapter. In nature, form usually follows function, so understanding the function of a memory system will help us ultimately understand its operating form.

3 Memory researchers understand that certain stimuli are easier to remember than others—e.g., pictures are usually remembered better than words. But these differences are assumed to reflect the richness of the stimulus features, or the availability of relevant retrieval cues, rather than any kind of specialized mnemonic tuning. Few would argue, for example, that our memory systems specifically evolved to process and remember visual events (for a possible exception, see Paivio, 2007).

4 Again, predicting optimal performance in such cases is not a direct test of evolutionary theory. Adaptations evolve subject to nature's criterion but need not work optimally when faced with the problems that led to their development. It is a reasonable hypothesis to pursue, however—one that leads to *a priori* predictions about cognitive performance.

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2

FORGETTING AS A FRIEND OF LEARNING

Robert A. Bjork

It is natural to think that learning is a matter of building up skills or knowledge in one's memory and that forgetting is a matter of losing some of what was built up. From that perspective, learning is a good thing and forgetting is a bad thing. The relationship between learning and forgetting is not, however, so simple, and in certain important respects is quite the opposite: Conditions that produce forgetting often enable additional learning, and learning or recalling some things can contribute to forgetting other things. In this chapter I focus on why forgetting enables, rather than undoes, learning.

Among his multitude of contributions to research on human learning and memory, Larry Jacoby was among the first to emphasize that forgetting can facilitate learning. In an important early paper (Jacoby, 1978; also see Cuddy & Jacoby, 1982), Larry characterized restudying after *not* forgetting as "remembering the solution" and restudying after forgetting as "solving a problem"—that is, again carrying out activities that have the potential to enhance subsequent retention. I discuss Larry's arguments and results later in this chapter.

My own interest in the relationship between forgetting and learning goes back to my graduate-student days at Stanford University, during the heyday of fitting learning and memory data with multi-state Markov models. David Rumelhart and I (Bjork, 1966; Rumelhart, 1967) got caught up in the challenge of trying to account for the trial-by-trial short-term-memory and long-term-learning effects of any arbitrary spacing of successive inter-trial intervals during paired associate learning. The idea behind what became my dissertation was to do away with the usual constraint that a given pair in a to-be-learned list of paired associates does not come up again until the next cycle through the list—a constraint that makes short and long intervals between successive presentations of a given item very infrequent. Instead, I let each successive interval for a given pair be determined