Introduction:

The Adventure Begins

Learning is an adventure—and as anyone who’s survived an

adventure will tell you, that’s not always a good thing. It can be a

long, rewarding process that changes the way you experience the

world and reveals capabilities you never knew you had. But in the

retelling adventures are extolled only by the victors. For every

adventurer who’s slain an educational dragon, there may be dozens

lying in caves and ditches nearby, smoldering in their armor, ruing

the day they made their attempt.

My closest scrape with outrageous educational misfortune came

at the Indian Institute of Technology, Kanpur. The moment stands

out in my memory with uncanny clarity, as though it had been

filmed at double the standard frame rate, as in Peter Jackson’s

somehow-too-vivid Hobbit movies. It happened my final year at

university.

Actually, to be technical, it was the summer after my final year.

Although I had entered university firing on all cylinders, at some

point my straight As gave way to curvier letters, and finally, just

before what should have been my graduation, I managed to flunk

Controls, a course required for my engineering degree.

That meant summer school: one chance at redemption. In most

of India, summer means the monsoon season. In Kanpur, it’s wetter

than it is hot—and it is as hot as anywhere I’ve ever lived. The

dormitories weren’t air-conditioned, but the rooms did have French

doors that opened onto a small terrace, and so, like every other

sucker lucky enough to be taking remedial summer courses, I

pushed my bed close to the French doors, so that at least my upper

half could enjoy the occasional breeze. My worldly goods—my trunk

of clothing, books, a stash of sweets I’d brought from home—went

at my feet, at the other end of the room.

One morning, I woke up at eight or so, bleary eyed. Something

was amiss.

Or rather, something was looking at me. Something with an

impressive set of teeth.

I don’t know if you’ve ever experienced the rapid transition from

drowsiness to abject terror, but I don’t recommend it. Every part of

my body froze except my eyeballs, which swiveled on their bearings

to take in my visitor. Staring back, fangs bared, was a rhesus

macaque.

Too late, I realized my error: I had situated myself between my

stash of sweets and any passing hungry simians.

Monkeys, in my opinion, are cute only on the other side of a

television screen. They can be mischievous in all the worst ways,

even violent, and they sometimes carry rabies. We stayed like that,

face-to-face, for what felt like minutes. I pictured my obituary:

Once-Promising Student Mauled at Summer School.

Five years earlier, in high school, no one who knew me would

have predicted such an ignominious fate. Together with about

70,000 of my peers—the comparable number today is on the order

of a million—I had sat for the Indian Institutes of Technology’s

entrance exam. It was, and remains, perhaps the most competitive

exam in the world. With some variation by year, only the top

2 percent of test takers are accepted to any of IIT’s campuses, which

means for every fifty would-be dragon slayers, only one prevails.

When my cohort’s scores came in, I learned that I had placed among

the top five hundred students in the country. The news came as a

major relief. Though I had won the neonatal lottery in the sense

that I had been born to educated parents who prized learning and

independent thought, we were far from wealthy, and they had made

it clear to me that if I were ever going to make something of myself,

academic excellence would be non-negotiable. After I saw my name

on that board, it seemed my adventure was off to a promising start.

But at some point at university, the going became a slog. It

became difficult to figure out how and why the abstract coursework

I was supposed to be learning mattered in the larger scheme of

things. It wasn’t my professors’ fault; I was being taught by some of

the better professors in India, and plenty of other students were

doing just fine. And it wasn’t that I didn’t want to care about the

material. I wished desperately, in fact, for the stuff I was being

taught to fit into my head as effortlessly as it had in my childhood.

But instead, for the first time in my life, learning had become

difficult. In a way, I almost envied the monkey slavering at the end

of my bed. All he had to do was wander along the row of dormitory

windows and take whatever food was on offer. To him, my

university was a buffet, filled with treats just waiting to be

discovered. It should have been that way for me as well. I could see

some of my friends partaking in the spread of knowledge, but I

couldn’t force myself to eat. In a very real sense, the monkey was

better adapted to my university than I was.

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Today, more than thirty years later, I’m happy to report I survived

the most dangerous part of my educational adventure. The macaque

at the end of my bed scampered away, permitting me to spend the

rest of the summer forcing down the curriculum of my Controls

course (and reading J. R. R. Tolkien’s entire Lord of the Rings

cycle). If I hadn’t been given that second crack at that course,

however, or if something else should have come between me and

my studies that summer, I shudder to think about the later

educational journeys I would have missed out on.

Instead, today I find myself in a unique position: not just

engaged in my own lifelong pursuit of knowledge, but also the lead

guide for many others. I head the Open Learning effort at the

Massachusetts Institute of Technology, where it’s my job to fling

open the doors of the MIT educational experience and extend

aspects of it to as many people as might conceivably benefit.

My quest is hardly unprecedented. Many others across time and

space have made similarly ambitious attempts: geniuses,

visionaries, disciplinarians, anti-disciplinarians, administrators,

philosophers, gurus, literal saints.\* Some failed, some succeeded

with certain types of students in certain conditions, and some saw

their ideas spread nearly worldwide, only to recede. And so it would

not be unreasonable to wonder what I, and the groups that I

represent, bring to the equation that is so new and different. It can’t

be just my experience as an educator, although, if I may be so

immodest, I am a good one. And it can’t come down just to the

transformative new education technologies being created at MIT

and elsewhere. After all, would-be reformers have overhyped

education tech for well over a century. To William Rainey Harper,

who taught Hebrew at Yale University in the late 1800s, the

transformative technology was the United States Postal Service,

which he claimed would facilitate correspondence coursework

“greater in amount than that done in the classrooms of our

academies and colleges.” In 1913, Thomas Edison voiced similarly

high hopes for the motion picture, which he thought would render

textbooks “obsolete.” Next came radio, which was supposed to

become “as common in the classroom as the blackboard,” then

television, which 1950s-era technophiles referred to as “the 21-inch

classroom.” In 1961, Popular Science predicted that by 1965, half of

students would rely on automatic “teaching machines” for their

instructional needs. By the 1970s and 1980s, computers had become

the new top contender. And indeed, although they did soon become

“a significant part of every child’s life,” as the MIT educational

technology pioneer Seymour Papert foresaw in 1980, they have yet

to live up to his 1984 prediction that “the computer will blow up the

school.” Far from it: Despite the onrush of technological changes

that have come to education since the middle of the nineteenth

century, most of us still teach and learn in classrooms that remain

remarkably similar to those of 150 years ago.

And so, when I ponder what education could become, I find my

thoughts wandering less to hypothetical, technological futures than

to my own past: to my university dormitory and that monkey, for

whom the physical architecture of standardized education spelled

nothing but opportunity. In the course of my own journey, I would

come to realize that those same sorts of educational structures—

encoded not just in architecture but also in software, laws of the

land, traditions, organizational rules, and unspoken norms—had

ceased to function as a playground for my mind, and had begun to

constrain my ability to learn. Many others had it worse. My most

critical moment of distress had arrived late enough in my education

that, with plenty of family support and few responsibilities of my

own, I’d managed to muddle through. I had been one of the lucky

ones.

ENTER THE EDUCATIONAL WINNOWER

I’m hardly the first observer to note that standardized educational

structures, ostensibly put in place to nurture learning, can in fact

impinge on it. In fact, a surprisingly wide variety of education

reformers find common ground not just in their broad antipathy to

the educational status quo, but also in how they describe it—which

is to say, by analogizing schools to factories. As Alvin Toffler wryly

noted in his 1970 book Future Shock, “the whole idea of assembling

masses of students (raw material) to be processed by teachers

(workers) in a centrally located school (factory) was a stroke of

industrial genius.” Today, you can find reformers of virtually all

stripes inveighing against the so-called factory model, from the free-

marketeers at the Clayton Christensen Institute (“The factory-

model system” processes “students in batches”) to the left-leaning

Century Foundation (“The ‘factory’ model…tends to alienate

teachers on the front lines”). Centrists, such as the Learning Policy

Institute, have echoed the metaphor, and so has the arch-libertarian

John Taylor Gatto, who describes school as “a kind of halfway

house” preparing youngsters for “service to a mind-destroying

machine.” Tech evangelists, too, have hopped on the bandwagon: As

Salman Khan, an MIT alumnus who created the Khan Academy

educational video series, has said, “There is no need to continue the

factory model inherited from 19th-century Prussia.”

To the credit of all these critics, the standardization of school

does indeed come with serious drawbacks. And yet, for all its

prevalence, I still don’t think the factory metaphor provides the best

illustration of what mass-education-as-we-know-it does to learners.

For one thing, education reformers have been leveling similar

complaints for a very long time. As the historian Sherman Dorn has

pointed out, even as early as the decades leading up to the Civil War,

American schools were replete with many of the supposed sins of

today’s “factory model,” including mass-produced textbooks and a

tradition of learning by rote. A wide wave of reforms took place, and

yet, by the tail end of the nineteenth century, a new generation of

reformers was already issuing complaints remarkably similar to

those of their predecessors. This process repeated itself again and

again, in the Progressive Era and throughout the twentieth century.

In many respects, then, to rail against “factory-style” schools today

is merely to slap a fresh metaphor onto an age-old struggle against

repetitive, perfunctory instruction.

But still, it’s easy to see why the factory comparison is so

tempting. School, at a glance, appears to take in raw materials—

human beings, in all their variety—only to produce a sea of similar-

seeming graduates. It would only be reasonable to assume, then,

that a shaping, molding process must be taking place between

matriculation and graduation: clay, formed into dinner plates; gold,

cast into bars; trees, whittled down to toothpicks.

Nowhere is the resulting homogeneity more apparent than in

college admissions. In recent years, elite colleges in particular have

found themselves with the strange problem of differentiating

among students who, on paper, are essentially clones—at least in

such still-important terms as their SAT and ACT scores and grade

point averages. The product of the supposed “factory,” at least when

viewed through its preferred lens of standardized metrics, is

undeniably consistent.

But molding isn’t the only process capable of churning out such

homogeneity. To the extent that the output of educational systems

around the world differs from the input, it seems to me that a

different procedure is just as responsible, perhaps more:

A winnowing.

By blowing air through a column of crushed seeds, a winnower

can separate seeds from their shells, or grain from chaff. Small

winnowers can take up as little space as a vacuum cleaner and can

be kept in the corner of a bakery or coffee roasting shop. Large ones

can be the size of a warehouse: an entire factory devoted to

producing near-identical grains on an industrial scale not by

molding or shaping, but by eliminating deviance. When building

such a device, the question is always what level of error is

acceptable. How much good grain is worth throwing out in order to

achieve next to no chaff in the final product?

It’s hard to pinpoint precisely how much raw human potential

the global educational winnower routinely sacrifices for the sake of

a consistent product, but there’s every reason to believe the wastage

is vast: a world’s worth of attrition parceled out most visibly in

rejection letters and underwhelming test scores, but also in less

obvious forms: courses never taken, applications never sent,

examinations never sat for, books never read.

Once you realize how education systems are set up not just to

nurture, but also to cull, you begin to see it everywhere. We winnow

in how we test, and we winnow in how we teach.

We also winnow, for that matter, in who we teach—and where,

and when, and for how much. Take the widest possible view and try

to imagine everyone in the world who might want to learn

something via formal educational channels. Right from the start, a

whole slew of access-related factors cut short educational journeys

before they even begin. Maybe you’d like to take some higher-ed

courses, but you live too far away from a college or university, or

maybe you’re “too old” to go to school. (No such thing, but on the

other hand, holding down a day job certainly makes it harder to get

to classes during the workweek.) Maybe you’re a stressed-out

parent, or someone with intensive eldercare responsibilities. Maybe

you live in a region of the world without great schools, or your local

schools won’t admit people of the “wrong” race or caste or social

position. In some countries girls are denied full access to education;

in others, girls seem to zoom ahead in grade school only to be

stymied later in their journey, or shunted toward stereotypically

“feminine” fields while the boys get to play with robots. You might

not belong to a family that expects you to go to college, or you might

not belong to a community where higher education is the norm. As

the economists Caroline Hoxby and Christopher Avery

demonstrated in a 2012 study, a large number—“probably the vast

majority,” they write—of low-income, high-achieving American

students simply never apply to a selective college or university,

despite the increasing availability of generous financial aid

packages.

And because not everyone is granted generous financial aid, the

cost of education itself only adds capriciousness to an already

ruthless winnower. Since the early 1980s, the full “sticker price” of

college tuition has increased year in, year out, at more than double

the rate of overall inflation. There are a number of reasons why,

including the substantial administrative and physical-plant costs

posed by major research efforts, declining government funding, and

the economic fact that as salaries in high-tech fields rise, “high-

touch” fields like teaching and healthcare must keep pace if they

hope to stay in business.

But perhaps the most straightforward explanation for tuition’s

rise is the most persuasive: Simply put, the average undergraduate

degree is still well worth the cost. As the MIT economist David

Autor demonstrated in a 2014 paper in Science, pursuing a college

degree remains one of the smartest financial decisions you can

make, leading to a median lifetime benefit of roughly $500,000.

One slightly jaundiced way to look at the mismatch between

college’s cost and value, then, is to recognize that the sticker price

could, if anything, be worse, since the market would largely bear it.

Indeed, one intriguing, model-based analysis, created by the

economists Grey Gordon and Aaron Hedlund, supports this idea.

They argue that broad, continuing student demand may be the

primary driver of tuition increases: Because more students than

ever want to go to desirable colleges and reap the college wage

premium, while the number of seats at said colleges has remained

largely stagnant, the price has gone up. (Meanwhile, at lower-tier

colleges whose degrees don’t confer much of a wage premium, you’d

expect to see declining enrollment—and that’s precisely what’s

happened in recent years, a trend that has hit for-profit colleges

particularly hard.)

Despite the rise of needs-blind admissions and the best efforts of

colleges and universities to provide significant financial aid, the cost

factor still winnows away lower-income students with callous

efficiency. The relationship between family income and college

attendance is almost absurdly strong, as a team led by Harvard’s Raj

Chetty showed in 2014, with 25 percent attendance at the lowest

income rung rising straight as an arrow up to 95 percent attendance

at the highest income level. Worse, the lower your family’s income,

the less selective the institution you’re likely to attend—

a consequence not of differences in aptitude but rather of such

concerns as the need to be close to home to help family members,

or difficulty jumping through all the hoops required to put together

a top-tier application package. Although in raw terms, less-selective

colleges account for more of the U.S.’s income mobility than elite

schools, elite schools have the edge on a per-student basis, and tend

to offer better financial aid and support resources to boot.

“Ironically,” Stanford’s Hoxby has said, lower-income students “are

often paying more to go to a nonselective four-year college or even a

community college than they would pay to go to the most selective,

most resource-rich institutions.”

Any plan to expand the learning horizons of people everywhere

must involve recalibrating the educational winnower to be more

inclusive, so that we stop turning away learners for such access-

related reasons as income, geography, and timing. Necessarily, such

a plan would involve adding “seats,” be they physical or virtual, to

the world’s top-notch classrooms, for which demand is already high

and growing. One force at odds with adding seats, however, is the

all-too-prevalent idea that for a school to be top-notch, it must be

“selective”—meaning it turns away most of its applicants. And

therein lies a conundrum.

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In fact, selectivity itself, and how we go about enforcing it,

represents one of the more powerful, pernicious ways that our

educational winnower squanders human potential. Slotting the best

students into highly sought-after seats is, in its way, an admirable

goal—after all, we should make the most of our limited resources.

But the way we pursue that goal is built on a set of glaring

assumptions: that our potential as learners is both knowable and

fixed, more or less for life, perhaps starting as early as birth. These

ideas, though highly debatable, comport with how most of us think

about intelligence: If you’re smart now, you’ll still be smart in ten or

twenty years. Or, as Lewis Terman, the father of American

intelligence testing, wrote in 1919, “the dull remain dull, the average

remain average, and the superior remain superior.”

The original inventor of the intelligence test, the French

psychologist Alfred Binet, disputed this sentiment. Binet was

convinced of intelligence’s fungibility. In fact, the whole point of his

test, which he invented in 1905, was to identify members of the

population whose intelligence might benefit from intervention.

Soon, however, his test was coopted by Terman and like-minded

thinkers, who approached the topic with a worldview steeped in the

deeply unfortunate tradition now known as “scientific racism.” Such

scientists, in constant search of evidence that could prop up their

prejudices, considered it a given that human intelligence was

“chiefly a matter of original endowment,” as Terman put it. “We

must protest and react against this brutal pessimism,” Binet

lamented in 1909, to no avail. Within a decade, such pessimism was

quite literally on the march. IQ tests, given to 1.7 million U.S. Army

servicemen in World War I, led to the development of a National

Intelligence Test for schoolchildren. By the 1930s, schools were

testing for IQ and aptitude as a matter of course. They often started

young; Terman insisted that “the limits of a child’s educability can

be fairly accurately predicted by means of mental tests given in the

first year” of school, and “accurately enough for all practical

purposes by the child’s fifth or sixth year.” Schools used the results

to sort students into tracks: the high road being the “college track”

or “academic track,” as opposed to lower “general” or “vocational”

tracks. Upper-track kids applying to college then found themselves

facing yet another cousin of the wartime testing program: the

Scholastic Aptitude Test, known today as the SAT, which began

classifying students according to their supposed aptitude in 1926.

To give aptitude tests like the historical SAT their due, they can

and do deliver a subset of learners from the jaws of the winnower.

For generations now, by establishing a point of comparison across

high school students, they have helped make admissions less

contingent on personal connections (even if that transformation

remains incomplete, given the extra consideration commonly

granted to, say, legacy applicants). A good test score, meanwhile, can

encourage students to give college a shot who otherwise might not.

(Indeed, when the state of Maine began requiring students to take

the SAT in 2006, 10 percent of students who would have otherwise

skipped the test ended up attending a four-year college.) And,

despite scientific racism’s formative role in aptitude testing’s

history, a well-aimed aptitude test can actually expose racial bias in

schools. In 2005, for instance, when Florida’s Broward County

introduced a universal, aptitude-based screening program to fill its

third-grade “gifted” classrooms, instead of relying on parents’ and

teachers’ nominations as in years prior, the Black and Hispanic

populations of those “gifted” classes tripled.

But there are also problems galore to be found with intelligence

and aptitude testing. It’s impossible to gauge intelligence directly, so

IQ tests attempt to sketch its outline by sending test takers through

a battery of challenges, the combined results of which supposedly

reflect one’s cross-cutting intellectual chops. Some psychologists

doubt that there really is a deep, generalized factor undergirding

performance on all these sorts of subtests. IQ skeptics also like to

point out that intelligence testing almost inevitably comes with

blind spots and biases. Starkly drawn test questions fail to assess

such virtues as creativity and interpersonal skills, for instance—and

then there’s also a long history of test makers coming up with

questions that favor test takers of higher socioeconomic status (for

example, “Define regatta”).

But let’s suppose, for argument’s sake, that these caveats don’t

matter much: that IQ scores really do paint an accurate picture of

one’s ability to learn. Even then, the predictive power of IQ scores

still comes up short, because IQ is not, as Terman supposed, fixed

for life. Rather, Binet was right: IQ is alterable, fungible, contingent

on your surroundings and experiences. Sorting students by IQ-style

tests, then, can be a recipe for winnowing out students for their

environmental circumstances, not their intrinsic aptitude. In fact,

speaking in aggregate, the lower a family’s socioeconomic status,

the more variable (and therefore less heritable) IQ tends to be

within that family—which implies that environmental factors wield

particularly disproportionate influence over IQ scores in lower-

status populations. Such external factors can be either helpful or

harmful. Pollution, for instance, such as lead in drinking water or in

the air, can take a lasting toll on IQ, as can childhood malnutrition,

as well as childhood abuse and neglect. More temporarily, lack of

sleep and acute stress can take a severe bite out of the cognitive

processes required for good performance on IQ and other

standardized tests. On the bright side, education can boost IQ: On

average, every additional year of schooling you complete will garner

you between 2.7 and 4.5 IQ points.

So malleable is intelligence, in fact, that the simple act of

teaching students that it can improve—leading them toward what

the psychologist Carol Dweck calls a “growth mindset”—can, in

specific circumstances, cause noteworthy achievement gains.

Perhaps the most obvious sign, however, that tests of intelligence

and aptitude measure something fluid, not fixed, is the sheer scale

of the test-prep industry that crops up whenever the stakes of such

exams are sufficiently high. As the education historian Carl Kaestle

has written, “Generations of affluent people buying test preparation

to improve their children’s ‘aptitude’ would prove the naïveté of

calling the SAT a measure of ‘aptitude.’ ” In the summer of 2019, in

an attempt to mitigate such distortionary factors, the SAT-issuing

College Board briefly announced that it would begin contextualizing

its scores with information about test takers’ neighborhoods and

schools of origin, before walking the plans back a few months later.

The tentative step would never have been necessary had SAT scores

adequately represented aptitude in the first place.

Despite the continued influence of the SAT in college

admissions, starting in the 1980s the American education

establishment began to lurch away from aptitude exams and toward

subject-matter-specific “achievement” exams, which test not for

intelligence but rather acquired knowledge and skills. As these

customs changed, a wave of bowdlerization washed over aptitude’s

remaining edifices. In 1993, the College Board changed the name of

the SAT from “Aptitude Test” to the redundant “Assessment Test,”

and then, in 1997, did away with the words behind the letters

entirely; SAT now stands for nothing in particular. Meanwhile, high

schools’ “college” and “general” tracks have slipped into a suit of

subtler terminology: Advanced Placement and “honors” courses

now form the rails of a college track that exists in all but name.

I wish I could reassure you that backward-facing achievement

exams winnow away learners far less arbitrarily than forward-

looking aptitude tests, but it’s not clear they do. Acute stress, for

instance, impairs cognitive processes that are indispensable for both

sorts of exams. And then there’s the matter of stereotype threat: the

well-supported theory that negative stereotypes can provoke unfair

distractions, doubts, and anxiety in students belonging to

disadvantaged groups, harming their performance on high-stakes

tests. Take, for instance, a group of boys and girls who, in 2013,

posted identical scores on the Specialized High School Admissions

Test, the sole criterion for entrance to eight of New York City’s most

selective public high schools. The following year, the girls went on

to earn significantly higher GPAs than the boys, a sign that

something about the entrance exam had disproportionately

depressed the girls’ scores. Perhaps the issue was that they were

less willing to guess at answers than the boys, but it was just as

likely that stereotype threat had erected an asymmetric distraction

during the test—occupying girls’ cognitive resources at precisely the

moment when they needed them most.

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If a learner’s personal circumstances act like a thumb on the scale

determining whether she’s worthy of educational investment, and

the biased methods used to sort students act like another, then

there is, improbably enough, a third thumb (or perhaps a big toe) at

work as well. It has to do with how we expect students to learn.

In even our best-intentioned attempts to shovel information into

students’ heads, educators routinely violate principles found

throughout the research disciplines collectively known as cognitive

science, from higher-order psychology down even to the molecular

level. Every one of these violations—often the unintended

consequence of scholastic norms and structures—comes at the cost

of learning adventures delayed, diverted, or cut short.

Put simply: In our efforts to standardize education, we’ve made

learning too damn hard. This unfortunate state of affairs harms

students across the board, and may be especially fraught for

disadvantaged groups who arrive in classrooms already stressed,

especially vulnerable to the worst effects of biologically and

psychologically unsound instruction. One powerful way to save vast

swathes of the world’s unduly winnowed learners, then, may be as

simple as making learning more user-friendly, by identifying and

eliminating unnecessary cognitive fetters.

Happily, I’m here to report that there are many feasible ways to

do precisely this—not by watering down the knowledge and skills we

hope to impart, but rather by deliberately rethinking how we teach,

and how students might strive to learn. Such an approach would

certainly not resolve deep, systemic biases, but nevertheless it

stands to mitigate some of the excesses of our overzealous

winnower. Tailoring education to meet the specific, often surprising

demands of the equipment between our ears will permit us to

increase the depth, breadth, and rigor of learning—for a far wider

population of students than currently benefits.

TO TEACH—OR TO SORT?

It’s fitting that the modern science of learning may help pull us out

of our current predicament, because its forebears certainly helped

shove us into it. During the first few decades of the twentieth

century, many of the emblematic features of contemporary mass

education entered into widespread use while others, predating that

era, were put to work in newly standardized ways. Abetting and

inspiring this infrastructural sprawl was the young field of

experimental psychology, which had begun to draw sharp,

quantifiable edges around the once-gauzy phenomenon of learning.

In 1898, the experimental psychologist E. L. Thorndike declared

to the world that learning came down to principles of mental

association. He argued that when people—or, in the case of his

original experimental subjects, hungry cats—do something that

results in a desirable outcome, they become increasingly likely to

repeat that action. In such instances, he maintained, a mental

association forms: between a lever on the door of a cat’s cage, say,

and a tasty meal outside. As I’ll explore in chapters ahead, using

such fundamental building blocks, it’s possible to posit an entire,

freestanding theory of how human learning works, including in the

classroom. (Instead of “lever” and “cat food,” for instance, students

might associate “5 times 7” with “35.”) By chopping up learning into

manageable, measurable chunks, Thorndike’s theory created a

scientific rationale for the standardization of schools, and his

theories came with certain other attendant assumptions as well—

about students. His model was, in essence, a new take on the old

notion of the mind as blank slate, shaped by experience as opposed

to innate predispositions. Thorndike’s version, however, came with

a near-Orwellian twist: Although all slates were born blank, some

appeared to be more blank than others—or at least better able to

absorb and parse incoming information. Like his contemporaries in

the IQ-testing game, he believed this capacity to be both genetically

determined and set for life, an idea that added considerable heft to

the twentieth century’s obsession with testing and sorting students.

(Indeed, Thorndike and Terman worked together on both the

Army’s IQ testing program and the follow-up National Intelligence

Tests.)

And so, even while some of his contemporaries were arguing

that the purpose of education was to improve intelligence,

Thorndike saw things differently. “The one thing that the schools or

any other educational forces can do least,” he told his students at

Columbia University, was develop “powers and capacities.” In a

world where intelligence wasn’t improvable, he recommended that

schools focus their limited resources on those students best able to

make the most of what they were given. It was imperative that

schools winnow the chaff from the wheat.

It’s hard to overstate the degree to which such assumptions

became woven into the fabric of mass education in the United

States, and much of the rest of the world, as the twentieth century

wore on. Even today, many schools begin sorting students as early

as the end of elementary school, as though their promise as learners

were both set for life and entirely knowable. (It’s neither.) We

attempt to fill them with facts as though their heads are an empty

bucket. (The better metaphor, as I’ll explain later, would be a

growing tree.) We spur them to learn with carrots and sticks like

GPAs and test scores. (Instead, we could focus on building natural

interest and curiosity.) Finally, at the end of this process, a very

specific sort of student is left standing—someone who is in no way

undeserving of further educational investment, but who is also in

no way representative of the full scope of human potential that

went in.

Even as mass-education structures crystallized around

Thorndike’s point of view, however, the field of cognitive science

continued to advance, creating a gap between the leading edge of

scientific knowledge and the increasingly outdated assumptions

frozen at the core of standardized education. The issue wasn’t that

Thorndike was wrong. Rather, his theory of learning turned out to

be reductive: an oversimplification of what we now understand to

be an extremely complex process. In fact, the learning mechanism

that Thorndike theorized bears more than a passing resemblance to

today’s most commonly accepted neuroscience model for how

information is represented among the brain’s synapses—a

remarkably prescient finding. What he failed to anticipate, however,

was that his model might compose only the ground floor of what

many cognitive scientists now think of as a high-rise of sorts, with

individual neurons and their synapses supporting the activity of

specialized regions of the brain; the physiological brain supporting

psychological processes; physio- and psychological processes both

contributing to what we think of as the conscious mind; and above

that, multiple minds interacting with each other in classrooms and

beyond. At every one of these levels of organization, researchers

have uncovered processes that turn out to be absolutely critical to

successful learning—and which, when interfered with, can quickly

bring an educational adventure to a grinding halt.

Many of our inherited education practices, with their hundred-

plus-year-old underpinnings, sit uneasily with these newer findings.

If my mission to foster learning far and wide is to have a prayer of a

chance, it must avoid replicating these same old mistakes on a

larger scale. Rather, we must first undertake a cognitive reckoning

of sorts. Based on what we now know about the levels of the

learning brain and mind, what—as teachers and learners both—can

we do to make the act of learning more user-friendly?

—

Perhaps the most obvious impediment to making learning easy is

the pervasive notion that learning should be difficult. This idea is as

prevalent at MIT as anywhere—perhaps more so. As an informal

slogan, MIT’s undergraduates have adopted the initialism

“IHTFP”—short for “I Hate This F\*\*\*ing Place,” intoned usually (but

not always) with a rueful smile—which gives you one good

benchmark of how taxing they find their coursework. Challenging

students to develop rigorous, deep, and readily activated bodies of

knowledge is essential. Imposing onto this already difficult

undertaking additional, unnecessary hardship, however, is both

cruel and arbitrary—like requiring Olympic sprinters to first qualify

in a karaoke competition.

And yet, another of MIT’s cherished tropes hints at precisely this

sort of needless difficulty. It’s long been a point of masochistic pride

that learning at MIT is like drinking from a high-pressure fire hose.

Our students, this bit of campus lore suggests, are smart and tough

enough to gulp down a flow of information capable of stripping

paint. And so, in 1991, when a group of pranksters set up a water

fountain on campus that literally dispensed drinking water from the

tip of a fire hose, MIT made it into a permanent exhibit. The fire

hose fountain now graces the entrance to the Ray and Maria Stata

Center, the building where most of MIT’s computer scientists live,

with a commemorative plaque explaining about high-pressure

learning. Every time I walk past it, I grimace, because the sculpture

suggests two misguided ideas. First, that apparently learning is a

difficult endeavor at MIT. That’s strange, considering that as the

world’s premier institute for technical education, blessed with an

utterly fantastic student body, you’d think we would find it easier to

teach. (And in fact, we are far better at teaching than the fire-hose

metaphor suggests.) And second, it implies that people who, for

whatever reason, are unable or don’t care to sip from the stream of

pressurized truth don’t belong at MIT. Indeed, perhaps advanced

education is not for them. Perhaps knowledge itself, beyond what

they catch as it flies by in the news and on social media, is not for

them.

Or more likely: We’ve been thinking about learning all wrong.

We’ve internalized the idea that learning is meant to be an ordeal

through which students must persevere or fail. I’d like to step back

and ask why. Human beings are built to learn. It would not be too

overdramatic, in fact, to argue that our learning ability is our

birthright as a species, hard won through eons of natural selection.

The difficult part should be over. When did the abstraction of useful

knowledge from the world around us become attainable only

through bitter perseverance? When did learning become not the fun

sort of adventure story, but a grim slog against the odds?

In an education system set up in part to sort the supposed elect

from the unworthy, any unnecessary impediment to the act of

learning itself will inevitably push a subset of students toward the

latter category: a flunked exam here, a denied college application

there, diminished educational prospects overall. More troublingly,

there’s every reason to believe that that subset—the winnowed—will

disproportionately consist of students who arrive at school pre-

burdened with the sorts of social and economic disadvantages I’ve

already discussed. One obvious, worthy response to such problems

is simply to fix them: to lead a full-frontal attack on poverty and

racism and sexism and all the other things that keep good people

down. In fact, if we ever hope to live in a more just society, such a

direct approach is simply non-negotiable.

But even in a world miraculously without such obstacles,

learners would still be hamstrung by cognitively clumsy instruction.

To truly make education as equitable as possible, it is imperative

that we shed the myth that serious learning must be difficult, and

find ways to make instruction far more cognitively user-friendly.

Such an approach would save students from undue winnowing

while helping others achieve new heights of academic excellence.

And if we can save a few students from the ruthless machinery

of the educational winnower, then perhaps we can also multiply

that effect, taking our new and improved approaches and making

them accessible to a wider world of learners. This is where new

instructional technologies come in. As the peddlers of earlier

technologies discovered the hard way, a hot new instruction

medium alone—even one capable of reaching vast numbers of

students—isn’t likely to drastically change how most people learn.

The idea of using educational technologies as a vehicle for a more

brain-friendly mode of education, though promising, isn’t exactly

new, either. But as I explore in the pages ahead, both our

understanding of how learning works and the capabilities of new

instructional media have reached a point where their combined

potential raises possibilities too promising to ignore.

Let me say this before we go any further: I believe the best

education is still a human-to-human education, and I don’t see that

changing anytime soon. We’re only now, however, starting to see

what great human teachers can accomplish while wielding truly

powerful education technologies—especially when given the

freedom to act outside the inherited, often procrustean structures of

traditional mass education.

The need for more user-friendly, accessible learning has never

been more urgent. Admittedly, in saying this, I’m guilty of the long-

standing, unfair practice of dropping off the world’s problems at the

classroom door for educators to solve. But the fact is, the current

moment does present a suite of issues that demand uniquely

educational solutions. From the perspective of learners, the pace of

technological change is altering the rules of work, even as careers

are growing longer than ever. We need better, time-and-energy-

efficient ways for busy midcareer workers to keep current or change

tracks as needed. Meanwhile, at a time when intergenerational

income mobility has been stagnant for decades, we need new ways

to bolster one of the few forces capable of helping individuals vault

free of their parents’ circumstances: a college education.

And then there are the broader problems faced by entire

societies: climate change perhaps most existentially, but also such

concerns as pandemic disease, the medical and caregiving costs

facing countries with large aging populations, income and wealth

inequality, and finding ways to reattach gains in living standards to

economic growth, among many others. Unfortunately, we’re

devoting only a small portion of our collective brainpower to the

sort of innovation we’ll need to solve such pressing issues. Only a

small fraction of people is ever even given the chance to innovate.

In an attempt to probe who gets to participate in technological

innovation, Raj Chetty of Harvard and his team have shown that the

vast majority of patent-holding inventors fit an alarmingly narrow

profile: mainly boys from wealthy families and rich neighborhoods.

“These findings suggest that there are many ‘lost Einsteins,’ ” they

write, “individuals who would have had highly impactful inventions

had they been exposed to innovation in childhood—especially

among women, minorities, and children from low-income families.”

This innovation imbalance equates to less income for those

underrepresented groups and less innovative energy devoted to

solving the unique problems they experience. Just as alarming, it

means that in terms of the gigantic, urgent challenges facing

societies around the world, we’re fighting with one hand tied behind

our back.

Scientists, meanwhile, are making their most groundbreaking

discoveries later and later in their careers, likely because in any

growing area of research, it takes each generation longer than the

last to get up to speed. We need ways to hasten students’ journey to

the cutting edge of research, and we need people from more diverse

backgrounds taking part.

One answer to both problems is to make learning easier: more

user-friendly and far more accessible, for all different sorts of

people, all around the world.

One way or another, learning is going to be an adventure. It can

be a story of Herculean perseverance or it can be a voyage of joyous

discovery. By erring on the side of the fun kind of adventure, we

may help more people learn, and realize more human potential,

than we’ve ever seen.

My lucky position at MIT has given me insight into how this

could happen, and now it’s my pleasure to share it with you. In the

chapters ahead, you will meet the scientists, educators, and

engineers who are changing the way we’re thinking about learning,

on MIT’s own campus and beyond. If learning is an adventure, then

learning about learning may turn out to be one for the storybooks.

\* Such as Saint Jean-Baptiste de La Salle, who dedicated his life to educating poor children

in France and, in 1685, established what was likely Europe’s first teacher-training school.

Part One

LEARNING IS SCIENCE AND

SCIENCE IS LEARNING

- I -

THE LEARNING DIVIDE

It was the last day of February 2017, and Amos Winter, an assistant

professor of mechanical engineering at MIT, was warning the group

of sophomores in his afternoon lab section about the destructive

potential of their batteries. Though supposedly safe, in the unlikely

event of a sudden discharge, each of the lithium polymer batteries

scattered on the conference table possessed enough energy to

maim, even kill.

How much energy, exactly? “Go ahead—slam it into a

calculator,” he said. After approximately ten seconds, anyone who

had worked it out was keeping the answer to herself, so Winter

bounded over to a whiteboard. You know the capacity of the battery,

he explained, which came labeled in units of milliampere hours.

“You basically just add in time to figure out energy in joules,” he

said, and in short order, the answer was on the board: 13,320 joules.

“That’s the equivalent to lifting a Honda Civic ten meters off the

ground,” he said. “Imagine a Honda Civic falling on your hand”—

that’s the kind of damage an exploding lithium polymer battery

could inflict. If the casing on such a battery begins to bubble, he

said, chuck it in one of the lab’s many sand buckets and run in the

opposite direction.

In the absence of any such catastrophes, however, class would

continue to hum along as it had for the first few weeks of the

semester. In addition to the batteries, sitting on the table in front of

each student was a simple robot—two wheels and a skid designed to

drag along the ground—which would serve as a sort of training

vehicle, in anticipation of the more complex robots the class would

build later in the semester. On these practice bots, which Winter

dubbed “Mini-Mes,” the students would learn mechanical

engineering principles ranging from simple to complex. They would

start by learning to code a microcontroller (that is, a very small

computer) to run an electric motor; later, they would instill in their

Mini-Mes the capacity to navigate the world autonomously like

rudimentary self-driving cars. Along the way, they would learn not

just robotics knowledge and skills, but how to think like designers

and engineers. They would come to understand how to approach a

task creatively, to spot issues before they become serious problems,

and, perhaps most important, to gain a level of trust in their own

ability to guide a project from early phase, when there are

innumerable paths to a desired solution, to late, when there’s only

one best way forward.

That was the learning progression in theory, at least. In practice,

some of Course 2.007’s students were coming to it with more

engineering experience than others. Some had competed in high-

school robotics tournaments. (The best-known extracurricular

robotics organization, FIRST Robotics, had actually spun out of

MIT’s original version of Course 2.007, back in 1989.) And the

rumor mill had already made it known that one student, Alex

Hattori, had competed on BattleBots, a televised contest known for

its metal-on-metal violence. He and his teammates had sent a buzz-

saw-wielding robot the size of a manhole cover into a gladiatorial

arena, to wage war on opponents with names like SawBlaze and

Overhaul.

To the other 164 students who lacked such head starts,

these advantages were cause for real concern. In MIT’s charged

academic atmosphere, stress among students is a perennial issue,

and unnecessary competition, usually over grades, does not help.

Most of the time, the Institute works hard to dampen this instinct—

for instance, by abolishing grades in the first semester of freshman

year. But Course 2.007 is different. Competition is baked into it at a

deep level, and is the reason why it is arguably MIT’s most famous

undergraduate offering. At the end of every spring semester, the

course culminates in a robotics showdown, which draws hundreds

of spectators from across campus and beyond. The winner achieves

lifelong bragging rights, entering MIT Valhalla while notching one

heck of a résumé bullet point.

Brandon McKenzie’s gaze slid to his lab mates seated around the

table. A varsity swimmer who had competed in the Division III

national championship as a first-year and would return to the

championship series later in the semester, he had thus far

maintained a perfect 5.0 GPA despite spending eighteen-plus hours

per week in the pool. He was not used to the sense of falling behind,

and yet there was no shaking the feeling that others were several

lengths ahead of him in the race to build serious, competition-

worthy robots. He had come to 2.007 with next to no practical

robotics experience, and there were a few others in the same

predicament—Amy Fang, for instance, at the other end of the table,

and Josh Graves, Brandon’s roommate, teammate, and all-around

co-conspirator, at his right elbow. But then there were folks like

Jordan Malone, seated directly across from Brandon, whose

computer-aided-design prowess Winter would later describe as a

“super power.” (And that wasn’t even the most impressive thing

about him: Although he never brought it up unbidden, everyone

knew that Malone, a short track speed skater, had brought home

Olympic medals from Vancouver and Sochi, prior to enrolling at

MIT at age thirty.) And there was Zhiyi Liang—Z, for short—a joyful

mad-scientist-in-training who seemed to come to class every week

having produced a new mechanical marvel in his downtime.

Brandon expressed no animosity toward his fellow students; indeed,

he would become the lab’s most reliable source of fist bumps and

backslaps in the weeks to come. But then again, he didn’t feel any

animosity toward his swimming teammates either, and that

certainly didn’t stop him from trying to outswim them.

Winter doled out off-brand Arduinos: microcontrollers that

would inform the movements of the class’s Mini-Mes today and,

later, their full-fledged, competition-ready robots. That morning’s

lecture had concerned the mechanics of brushed, direct-current

motors, the simplest type of electric motor. Now, mere hours later,

Winter was taking his students’ understanding of DC motors as

given and demonstrating how they could be put to work. As Winter

blasted through a series of reasonably complicated concepts,

Brandon scrambled to take in his words while also adjusting his

Mini-Me’s physical wiring and fiddling with his Arduino’s code on

his laptop. He sensed he was in danger of sliding even further

behind.

“I felt a little discouraged,” he said later. Although Arduino’s

programming language, C++, was basically new to him, some of his

classmates seemed to know it “like the back of their hand.” He was

keeping up for the time being, but he knew that the moment his

attention strayed he would find himself stranded. This course had a

sink-or-swim quality to it that felt all too familiar. It was as though

he’d been chucked into the deep end of a pool but didn’t yet know

how to stay afloat. And although there were plenty of instructors

looking on, telling him how to keep his head above water, it was up

to him to apply that information in a way that actually worked.

Provoking that conceptual shift—from theory to practice, from

inert to activated knowledge—is what 2.007, at its core, is all about.

The course assumed its modern form in 1970, when a young

professor named Woodie Flowers took the reins. In the decades that

followed, as the beloved professor became a professor emeritus, he

took on local-celebrity status on campus, where he tended to pop up

periodically, Stan Lee–like with his trademark mustache and silver

ponytail, to speak about learning. Every time, he stressed a single,

crucial point: the difference between “learning calculus” and

“learning to think using calculus.”

To educators like me, who hope to produce students capable not

just of earning good grades but of exerting their knowledge in the

wider world, this distinction is of the utmost importance. But for

students accustomed to clean borders around their education—the

four edges of an eight-by-eleven worksheet, four walls of a

classroom, four-year progression through high school, then college

—it can be unsettling to step out into the messiness of the real

world, even temporarily. And so every year, while some of 2.007’s

students exult in the chance to get their hands dirty, others hang

back, sometimes for weeks, to get their bearings.

Across the table from Brandon, Amy Fang had already sized up

her classmates. Arriving at MIT, she later recounted, she found her

fellow students so intimidating that she decided that staying in the

middle of the pack was a perfectly worthy goal. “I try to be average,”

she said, laughing. For the moment, as she connected her

servomotor to her Mini-Me’s breadboard, any sort of noteworthy

success in 2.007’s semester-end competition seemed unlikely. A

decent grade would be challenge enough: 2.007 had no exams, and

success in the final competition itself would have no direct bearing

on grades. But the design of the students’ competition robots would

eventually come under close scrutiny, and in the meantime the

course’s significant homework load felt like a millstone. It came in

two parts: written homework—a weekly set of four tricky, multipart

engineering problems—as well as a weekly physical challenge that

students were charged to accomplish using their Mini-Mes. This

week, they had to submit video of their Mini-Mes heading forward a

preordained distance, performing a U-turn, returning, and coming

to a complete stop—all without any input from a remote control.

Later in the semester, some students’ robots would pull off

autonomous tasks of greater complexity, such as using a light

sensor to follow a line drawn on the ground.

As Winter explained about this path-following strategy, Mo

Eltahir, a student from nearby Lexington, Massachusetts, spoke up.

“It’s cool because every lecture is stuff you can think of to use for

the competition.”

Winter let out a laugh. “Would you go so far as to say you’re

learning?”

They were indeed. In the demanding weeks to come, they would

etch new memories more deeply than they probably knew—and not

just any old memories, either, but highly contextualized ones that

would empower them to both understand their world and influence

it. To encourage this process, Course 2.007 does away with many of

the problems endemic to traditional classrooms and lecture halls,

which have hardly budged over the course of more than a century,

and replaces them with something better.

In 1902, the educational psychologist and philosopher John

Dewey (“America’s foremost philosopher of his time,” his New York

Times obituary would eventually read) laid out the “typical evils” of

classrooms he’d observed. Such incorporeal subjects as

mathematics, separated from the objects and processes that

numbers represent, and geography, divorced from geological and

historical events, lacked “any organic connection with what the

child has already seen and felt and loved,” he wrote in his book, The

Child and the Curriculum. As passive recipients of knowledge-

made-inert, students went through the motions of school without

ever feeling truly motivated to learn, mainly because the stuff they

were being taught didn’t relate to their day-to-day concerns and

goals. Today, even when schools manage to better contextualize

what they’re teaching, the same central assumption still persists:

Students are expected to learn for the benefit of their future, not

present, selves.

Course 2.007 isn’t like that. First, thanks to its sink-or-swim

nature, students don’t have the luxury of a lazy, memorization-

based approach to studying. Rather, any theory taught in class can

and must be immediately applied—after all, if you don’t apply it,

your opponents will. In part because students thrill to the

experience of seeing their knowledge translate into real-world

engineering powers, and in part because there’s glory on the line,

the course’s ability to motivate learning is second to none. Even

students with a long history of doing the bare minimum\*1 wind up

inspired despite themselves, spending far more time in the lab than

is strictly necessary, screwdriver in hand, notebook computer open.

In the space of a single semester, the course launches experienced

hobbyists and the uninitiated alike toward professional mechanical

engineerdom in a way that is sometimes imitated but never, in my

completely biased opinion, exceeded.

Today, when I contemplate the task before me, my thoughts

never stray far from 2.007. At minimum, any education scheme

worth its salt must not only deliver knowledge, but do so in a way

that is highly engaging—and then activate that knowledge, so its

owner can do real work in the world. Course 2.007 vaults these bars

with plenty of clearance.

The problem is a matter of access. Course 2.007 is extremely

expensive to offer, costing MIT far more per student than each

would pay in tuition, even without financial aid factored in. This

owes in great part to the costs of keeping the laboratory up with the

cutting edge of fabrication technologies while still safe for novices,

which equates to a lot of highly trained personnel.

Pragmatically speaking, anyone hoping to provide an educational

experience of this caliber to vast numbers of people either must be

mind-bogglingly rich or else find a creative way to pull it off at scale.

After all, you can’t put a billion people through Course 2.007; even

if you somehow found enough teachers and built enough

laboratories, according to one back-of-envelope calculation I’ve

done, it would still cost more money than exists in the world.

It’s certainly possible, however, to disseminate knowledge on

that order of magnitude for far less: Wikipedia alone has done that,

for instance, to great and deserved acclaim. So has MIT, in our own,

smaller, way: Starting in 2001, through our OpenCourseWare

initiative, we’ve made essentially all of our course materials freely

available to anyone with an internet connection. But making

information available is not the same as providing an education.

And so you might reasonably ask: Can a scaled-up education

scheme ever replicate what a skilled teacher in a traditional

classroom can achieve, let alone the motivating, contextualizing

effect of Course 2.007? Will its students ever truly make the jump

from understanding calculus to thinking using calculus?

TEACHING MACHINES, TEACHING HUMANS

Would-be innovators have dreamed of distilling and mass-

producing the secret sauce of education for well over a century. As

early as 1912, the psychologist E. L. Thorndike, already well on his

way to reshaping how America thought about learning, mused: “If,

by a miracle of ingenuity, a book could be so arranged that only to

him who had done what was directed on page one would page two

become visible, and so on, much that now requires personal

instruction could be managed in print.” In 1953, the Harvard

psychologist B. F. Skinner, in many respects Thorndike’s intellectual

descendant, attempted to realize this science-fictional notion by

building a series of “teaching machines.” One of them can still be

found at Harvard, tucked away on the ninth floor of the university’s

William James Hall. The wooden, rectangular machine would have

covered most of a student’s desk while she worked at it, making her

way through the series of questions printed around the edge of the

paper disk inside. A small rectangular window in the machine’s

bronzed lid displayed a single question at a time as well as the

answer to the previous question, and a nearby aperture let the

student scrawl her answer longhand on a strip of paper tape that

emerged briefly from the machine’s innards before plunging back

in. She would compare each written response to the correct answer

and, by pulling a lever, mark herself correct or incorrect. (Teachers

could check students’ answer tapes for inconsistencies after the

fact.) Once she’d answered every question on the disk, it would then

spin more freely, stopping only to re-pose those questions she had

initially gotten wrong, a process that would continue until she had

answered every question correctly. Students would move along at

their own pace, advancing from one disk to the next. The education

revolution, Skinner believed, would thus be personalized. As one

student memorably put it, “The eggheads don’t get slowed up; the

clods don’t get showed up.”

Just to the right of the window where students recorded their

answers, the bronze surface of the teaching machine on display at

Harvard is worn down to the underlying gunmetal: the result of a

decade’s worth of wrists rubbing the same spot. As the 1960s gave

way to the 1970s, however, the hype, too, faded from teaching

machines, and Skinner’s invention vanished from both schools and

the national conversation. They had proved less effective in the wild

than in the lab, many in the public found them creepy, and much of

the buzz surrounding the mechanical devices was finding its way

over to electronic ones: computers and the nascent field of

educational software. But still, neither the original teaching

machine nor its computerized equivalents have ever transformed

the classroom as promised.

And why not?

Perhaps most egregiously, teaching machines and their

immediate electronic descendants were boring. Once the novelty

wore off, many students said they hated the things—a major

indictment of Skinner’s entire project. Although it can feel

momentarily gratifying to get answers right, and it’s often good to

move at your own pace, Skinner’s approach proved overly simplistic:

blind to larger concerns like motivation, contextualization, and

social isolation. Like his predecessor E. L. Thorndike, Skinner was a

reductionist, seeking to explain learning in terms of its most

fundamental constituent parts. To his credit, reductionism done

right is one of the most powerful conceptual tools available to

scientists; it’s what allows us to understand chemical processes in

terms of atomic physics, for instance, or the concept of temperature

in terms of the average kinetic energy of molecules. But “done right”

assumes that the fundamental particles and processes you’ve

isolated really do explain the workings of the larger system in

question. When reductionism goes wrong, however—when

scientists and engineers underestimate the complexity of a system—

disaster can result: airplane crashes, stock market crashes, and

everything in between.

Somewhere on the continuum between Skinner’s reductive

teaching machines at one extreme and the relatively holistic

approach of Course 2.007 at the other, something important clearly

gets lost. And that wouldn’t be much of a problem—except for the

fact that the structures of standardized education, guiding and

confining students and teachers both, happen to be built of the

same intellectual bricks as Skinner’s teaching machines. In fact, I’d

go so far as to claim that, to the extent that traditional classrooms

today successfully help their students develop deep, contextualized,

activated knowledge, it’s due mainly to the skill of teachers working

despite the limits imposed on their medium—many of which can be

traced straight back to Skinner’s intellectual godfather, E. L.

Thorndike.

What’s so striking, looking back, is how at the very same time

that Thorndike and his allies began pursuing the research thread

that would undergird and justify the form mass education took in

the twentieth century, a separate research thrust, built on a wildly

different scientific ethos, offered an alternate path—one far closer in

spirit, as it turns out, to Course 2.007. In fact, although the story of

education at the turn of the twentieth century features enough

characters to rival the greatest hits of Russian realist fiction, the

story of the science behind the education is a much tighter

narrative, boiling down mainly to a contest between two figures in

the nascent field of educational psychology. It did not end in a draw.

As the education historian Ellen Condliffe Lagemann has written, “I

have often argued to students, only in part to be perverse, that one

cannot understand the history of education in the United States

during the twentieth century unless one realizes that Edward L.

Thorndike won and John Dewey lost.”

Although the more obvious set of battle lines that formed

between the two scholars concerned educational practice, their

higher-level disagreement on how to conduct and apply science

itself will hold the greater significance for our journey in the pages

ahead. If we ever hope to usher in a vision of education at scale that

is not reductive but rather expansive—closer to 2.007 than teaching

machines—we must first plumb the scientific divide that separated

Dewey and Thorndike.

DEWEY’S LABORATORY SCHOOL

At the very tail end of the nineteenth century, the young field of

educational psychology was being pulled apart. Holding fast to one

side were the defenders of mental discipline, an archaic theory that

analogized the brain to a muscle in need of exercise, typically

achieved via rote practice. The content to be learned mattered less

than the effort involved in learning it, and so, strangely enough, the

tradition found its strongest advocates in the classics-enamored

educational old guard. Since you had to exert your mind on

something, their thinking went, it might as well be something in

Latin or Greek.

Leading the other side was one G. Stanley Hall, a psychologist

known for applying newfangled experimental techniques to a

worldview centered on Charles Darwin’s theory of natural selection.

In a plan that might sound downright reasonable to modern ears,

Hall wanted schools to put away the mental barbells and structure

their curricula instead around students’ natural interests. There was

a catch, however: “Interest,” as Hall defined it, amounted to a

peculiar mix of historical myth and biological fantasy. Far from

alone among academics at the time, Hall believed (white) Western

culture had achieved an advanced stage of development to which

other cultures and races could only aspire. Many educational

theorists (including the otherwise egalitarian Dewey) took this

unfortunate idea a step further, tracing metaphorical connections

between the development of children and the “development” of the

world’s cultures. Hall took it further still, believing in a hard,

biological relationship between the supposed stages of human

history and those of childhood.

The resulting pedagogical strategy was, in its way, nearly as rigid

as mental discipline. Elementary school, to Hall, should consist

mainly of play, stories, and the study of nature: the sort of activities

ancient, “primitive” societies got up to. Only at age eight, he

decreed, should reading and writing enter the picture, to correspond

with the historical origins of written language. However, because

“reason is only dawning” at that age, he wrote, teachers should

introduce abstract ideas only through rote memorization, and wait

until their students had surpassed the so-called Homeric Stage

before explaining the how and why behind those concepts.

Encountering the absurd contest between the champions of

“effort” and “interest,” as the two sides were known, both Dewey

and Thorndike sought to break it up. That wasn’t all they had in

common: Both turn-of-the-century education psychologists were

heavily influenced by William James, widely considered the

progenitor of American psychology; both taught as colleagues at

Columbia University in the early 1900s; and they even looked

somewhat alike, with dark, center-parted hair and impressive

mustaches. But the impression of similarity lasts only that long. To

linger on a superficial point, take their mustaches: Thorndike’s

triangular mustache looked as though he trimmed it with the aid of

a protractor, while Dewey at one time sported a bushy soup strainer

that, to a modern observer, might connote horses and six-shooters.

Dewey’s approach to educational research was just as unreservedly

bushy, reliant on relatively naturalistic methods of observation as

opposed to the stripped-down experimentalism that Thorndike

wielded with surgical precision.

Dewey’s debut in the American educational conversation took

the form of a widely read monograph arguing that both sides of the

effort-versus-interest dialogue were guilty of ignoring students’ true

interests. Might it be possible to begin the education process with

children’s “urgent impulses and habits,” he wondered, and then

nurture the growth of a larger body of knowledge around them?

That same year, Dewey opened the doors of the Laboratory

School at the University of Chicago to find out. William Rainey

Harper—the onetime professor of Hebrew at Yale who, if you recall,

waxed bullish on correspondence courses—had been tapped to

become the University of Chicago’s first president. Intensely

interested in pedagogy, he began assembling a dream team of

educational researchers, including both Dewey and his soon-to-be

collaborator, Francis Parker. The timing was perfect: Dewey, sick of

all the “general theorizing” around effort and interest, had begun to

mull a way of testing the various theories floating around the

education world—most importantly, his own. A school, he decided,

could function as a laboratory for the study of learning. “If

philosophy is ever to be an experimental science, the construction

of a school is its starting-point,” he wrote. “The school is the one

form of social life which is abstracted & under control.”

—

The key word was abstracted. Today, one typically encounters the

term in adjective form (an abstract oil painting), but Dewey often

used it as a verb, to signify how, starting at a very young age, both

learners and scientists actively strive to single out what is

noteworthy about the world around them. From infancy, he

reasoned, raw data wash over our senses, and to make head or tail

of it all, we begin performing observations and even subtle

experiments, like tiny scientists. “The native and unspoiled attitude

of childhood, marked by ardent curiosity, fertile imagination, and

love of experimental inquiry, is near, very near, to the attitude of the

scientific mind,” he wrote in 1910.

To Dewey, the distance between the sort of firsthand knowledge

children gain through personal experience and the secondhand

knowledge passed down generation to generation (algebra, which

snakes are venomous, the location of Des Moines) was significant,

but bridgeable. The educator’s challenge was to close this gap: to

help the child’s interest stretch from items she had abstracted for

herself to the pre-abstracted knowledge of her forebears—and thus,

wrote Dewey, “short-circuit for the individual the slow progress of

the race.” Crucially, by starting with students’ day-to-day concerns,

this approach had the capacity to make learning feel immediately

rewarding. It was a sharp break from the prevailing idea (then as

now) that school should be endured “as a preparation,” he wrote,

“for something else, or for future life.”

Well-planned experiments (including informal and

thought experiments) designed to abstract theoretical truths from

the concrete universe in all its messy, noisy glory, were the key to

the entire operation. The Laboratory School was designed to enable

such experimentation in several ways. Its students, natural-born

experimentalists, would be encouraged in their instinctive

endeavors. Its teachers would be given great leeway to experiment

with day-to-day pedagogical strategies, based on how the students

responded. And the school as a whole would serve as an

experimental test subject: to verify whether its approach could truly

lead children from their immediate interests to the wide base of

knowledge they would need in a rapidly changing world. All told, the

school would bear “the same relation to the work in pedagogy that a

laboratory bears to biology, physics, or chemistry,” Dewey

proclaimed.

—

The Laboratory School opened in January 1896, with a group of 16

students, including Dewey’s own two children, and two teachers. By

1902, it would swell to accommodate 140 students, 23 teachers, and

10 graduate-student assistants. The school devoted no courses

exclusively to reading, writing, or arithmetic. Rather, students were

encouraged to treat such fundamental skills not as an end goal for

learning, but rather as a means of solving whatever problems they

encountered. Cooking, for instance, provided “a natural avenue of

approach to simple but fundamental chemical facts and principles,

and to the study of the plants which furnish articles of food,” Dewey

wrote. Gardening gave the students the opportunity to perform

biological tests on the viability of seeds; smelting led to an

explanation for why charcoal burns hotter than wood. Students

made textiles from the ground up: they sheared sheep, carded and

spun the wool, and then wove it into garments.

Such methods might today be called “interdisciplinary,” but, as

Dewey liked to point out, the academic disciplines are actually

arbitrary constructs, none of which, he wrote, is “eternally set off”

from any other. The school’s approach, Dewey claimed, didn’t just

impart richly contextualized facts and skills, but also provided

students “with the instruments of self-direction” and taught them

how to work with others in their “miniature community, an

embryonic society.”

Dewey hoped the microcosmic community he was building at

the Laboratory School would give rise to “a larger society which is

worthy, lovely, and harmonious.” To this very day, historians debate

why this sunny vision never came to pass. It might be due to the

fact that Dewey left the school suddenly in 1904, just eight years

after its inception. Compared to the lofty heights of his ambitions,

the events leading to his exit seem impossibly banal, involving a

clash of personalities and charges of mismanagement against Alice,

Dewey’s wife, who was serving as principal. When Dewey left, he

was snapped up almost immediately by Columbia University, where,

starting in February 1905, he joined the philosophy department.

Although in a sense his career as a philosopher of education (among

other topics) was only beginning, his days conducting original

education research were over, which put his ideas at a disadvantage

in the decades to follow.

Another likely reason why his school plan failed to spread

beyond Chicago is that his ideas simply ran counter to the zeitgeist,

clashing against what society at the turn of the century was looking

for from its schools. Especially at a moment when E. L. Thorndike,

Dewey’s intellectual rival—and, now, colleague—was beginning to

offer an attractive alternative.

THE BASEMENT AND THE ATTIC

“I just cannot understand Dewey!” So proclaimed a frustrated

Edward L. Thorndike about his Columbia University colleague.

From the very start, despite having plenty in common, including

faith in the ability of experiments to plumb the mysteries of the

universe, Dewey and Thorndike built their respective worldviews

around antithetical assumptions. So irreconcilable were their

outlooks, in fact, that the pioneering psychological writings of

William James served as a Rorschach test for the pair, drawing out

their differences. When Dewey read James’s articles in the 1880s

(eventually collected in James’s 1890 omnibus book, The Principles

of Psychology), he saw clear support for a holistic approach to

experimentation. As James’s Principles made clear, the human

mind had evolved in a social setting. Attempting to divorce the mind

from that setting for the purpose of an experiment, Dewey

determined, would be just as futile as studying plant growth in the

absence of sunlight. A stand-alone human mind was simply too

small to experiment upon by itself, so Dewey built an entire

miniature community in order to have a system big enough to

study.

A chance encounter with James’s book would send Thorndike,

meanwhile, hurtling in the opposite direction, toward reductionism:

breaking systems down into their smallest component parts. To his

point of view, the learning mind was too large to think about as a

whole; insight would come only from isolating the smaller, simpler

mechanisms that made it tick.

As an undergraduate at Wesleyan University, Thorndike entered

an academic competition requiring him to read from James’s opus,

which he said he found “stimulating, more so than any book that I

had read before.” Perhaps most exciting were the two-hundred-odd

pages concerned with James’s experimental studies—an approach,

Thorndike quickly realized, that reverberated with power. The old

mental disciplinarian notion that memory constituted a “faculty”

improvable through exercise, for instance, fell to pieces under

James’s scrutiny. James had memorized 158 lines of the long poem

Satyr, by Victor Hugo, which, he recorded, took him about fifty

seconds per line. Next, over the course of a month, he memorized

the first book of Paradise Lost, which should have, in theory,

strengthened his faculty of memory to peak human levels, making

him the Usain Bolt of poem recitation. However, when he returned

to Satyr and attempted to memorize another 158 lines, each line

took him seven seconds longer than it had earlier. All those mental

gymnastics had not improved, and had possibly enfeebled, his

“faculty” of memory—that is, assuming such a thing even existed,

which was starting to appear doubtful.

Young Thorndike was enthralled. Philosophers had long

buttressed the sagging notion of a faculty of memory with wordy

arguments and flights of introspection, and it had stood

imperturbable for generations. Then along had come a lone

academic who, with a single swing of a well-aimed experiment,

brought the whole thing crashing down. When Thorndike enrolled

at Harvard to continue his studies in English and French, he made

sure to take a psychology course with James, and within a year he’d

set his sights on a doctorate in psychology.

Funnily enough, by the time Thorndike began pursuing his PhD,

James was in the midst of a shift away from experimental

psychology and toward a highly successful second career as a

philosopher. Nevertheless, when Thorndike needed a place for his

experimental chickens to roost—Harvard told him he couldn’t

experiment on human children, so he’d begun working with young

chicks—it was James who provided the nest, permitting the fowl to

live and undergo study in the basement of his family’s home.

Thorndike later wrote that he hoped the resulting “nuisance to

Mrs. James” was “somewhat mitigated by the entertainment to the

youngest children.”

It was the start of several formative years of research around

which Thorndike would build his most enduring theories of mind in

general, and learning in particular. At the time, psychology was still

mostly a qualitative pursuit, although there were a handful of

notable, quantitative exceptions (including Jameses’ memory study

and the work of the German psychologist Hermann Ebbinghaus,

another self-experimentalist, who catalogued how long it took him

to forget long lists of nonsense syllables). Thorndike, however, was

a zealous believer in the power of numbers—even over such unruly

subjects as newly hatched chicks. In the Jameses’ basement,

Thorndike built mazes out of textbooks and sent his downy charges

into them. The chicks with maze-running experience, he soon

observed, would complete the course faster than their naïve

colleagues.

Before completing his degree, Thorndike decamped (with his two

“most educated” chicks, as he described them) from Harvard to

Columbia, the leader in the nascent field of experimental

psychology. In Manhattan, he set up shop in the stifling attic of

Schermerhorn Hall to continue his animal experiments. He soon

graduated from chicks to stray alley cats (and sometimes dogs and

monkeys), and from mazes to “puzzle boxes” of his own design,

made of wooden slats. Inside them, Thorndike locked his hungry

study animals until they managed to open the box’s door by such

means as pulling on a loop of rope, stepping on a pedal, or

performing several of these actions in a specific sequence.

(Thorndike’s son later recalled that these boxes “would have

shamed Rube Goldberg.”)

“You’d like to see the kittens open thumb latches, and buttons

on doors, and pull strings, and beg for food like dogs and other such

stunts,” Thorndike wrote to Bess Moulton, the woman he’d

eventually marry, “me in the meantime eating apples and smoking

cigarettes.”

Thorndike quantified the behavior of his would-be escapees,

timing their progress while counting the behavioral actions that led

up to each successful attempt. In a cat’s first run-in with a puzzle

box, escape usually occurred only after protracted trial and error,

and was always a happy accident. In later attempts, however, as with

the chicks in their maze of books, experience paid off. Up to a point,

the more successful escapes a cat had under its collar, the quicker it

escaped. Learning, it was clear, was taking place.

But how exactly had this knowledge made its way into the cats’

heads? In 1898, at the astonishing age of twenty-three, Thorndike

laid out a theory to explain his observations. By all rights, his report

should have been a small thing—merely a precursor to the five-

hundred-plus publications, including fifty books, he would go on to

produce. And yet, as he wrote to Moulton, “I’ve got some theories

which knock the old authorities into a grease spot.”

Most egregiously to Thorndike’s mind, the “old authorities” in

the study of animal behavior had imputed powers of humanlike

reasoning to animals. He found this ludicrous; his escapees’

performance had improved only gradually, evidence that sudden

epiphanies played no part in their learning process. In his 1898

dissertation, Animal Intelligence (later revamped in an extended

1911 version), he gave an alternate explanation: Animals only ever

solved problems by means of trial and error, and committed their

solutions to memory only by repetition, or the “wearing smooth of a

path in the brain,” as he put it. Decades later, neurological research

would partially vindicate this idea, showing that the points of

synaptic connection between neurons involved in memory storage

do indeed grow stronger with repetitive activity—about as close as

you could come, physiologically speaking, to a brain pathway “worn

smooth” with use.

Eventually, Thorndike codified his observations into a set of laws

governing learning. The most important of these, which he dubbed

the Law of Effect, held that for an animal engaging in trial-and-error

exploration, any actions that registered as having a “satisfying

effect” become more frequent, while those leading to a

“discomfiting effect” become less so.

The implications for human learning were staggering. Homo

sapiens, he decided, though capable of flights of reasoning beyond

the ken of his caged cats, still relied on essentially the same

processes as his animal subjects when it came to encoding

memories. “These simple, semi-mechanical phenomena,” he wrote,

“are the fundamentals of human learning also.” Assuming other

factors were aligned in favor of learning (a ready and willing mind,

content-to-be-learned chopped up into digestible chunks, and a

schedule of repetitive practice), then the assumptions behind the

Law of Effect remained “the main, and perhaps the only, facts

needed to explain” human learning.

THE BIRTH OF BEHAVIORISM

The Law of Effect cast two shadows deep into the twentieth century.

One fell over institutions of mass education, where its influence

lingers to this day. The other crept across the scientific field of

experimental psychology, where it helped inspire a movement that

reigned for decades. In a 1913 address at Columbia, the Johns

Hopkins psychologist John B. Watson introduced the term

behaviorism to describe the research doctrine that Thorndike and

his Russian contemporary, Ivan Pavlov, had already mostly staked

out. True behaviorists, in Watson’s extreme definition, would seek

to explain the mind purely in terms of stimuli (events acting on an

animal) and responses (the animal’s observable behaviors),

ignoring or even denying the influence of intermediating mental

processes. According to this theory of learning—somehow even

stricter and more stripped-down than Thorndike’s—the only thing

that could reinforce a pairing between stimulus and response was

the frequency with which they co-occurred. In an attempt to provide

a behaviorist explanation for human phobias, Watson and his

assistant, Rosalie Rayner, conditioned a nine-month-old child

known to history as “Little Albert” to fear fluffy white lab rats (and

by extension, other fluffy things) by making a loud noise every time

one came near. Ultimately, it wasn’t these experiments that got

Watson fired, but rather his relationship with the twenty-one-year-

old Rayner, which turned romantic, led to Watson’s divorce, and

caused Johns Hopkins to show him the door. He spent the rest of

his career in advertising, and is credited with coining the term

“coffee break” for Maxwell House Coffee.

Behaviorism didn’t end with Watson, however. B. F. Skinner, the

inventor of the aforementioned teaching machine, soon took up the

standard, revivifying Thorndike’s animal research in the form of his

Skinner Box, in which animals performed various actions to earn a

food reward. His feats with pigeons alone are worthy of volumes:

He taught them to play Ping-Pong, for instance, by training them to

peck a rolling Ping-Pong ball off the far edge of a small table, and

then pitting them against one another. Skinner’s pigeon-training

efforts reached their acme of usefulness when, in the early days of

World War II, he developed a pigeon-powered guidance system for

American glide bombs. Trained to peck a photograph of a target to

be bombed, the birds were packed into a bomb’s nose cone, where

their heads were tethered in such a way that their pecking

movements would steer the bomb toward the real target, on the

ground. The scheme actually worked in trial runs, but was obviated

by the development of radar and never put into action. Decades

later, Skinner bemoaned the premature end of his pigeon program.

It hadn’t all been for naught, however: “We had been forced to

consider the mass education of pigeons,” he said, and the lessons he

had drawn, like Thorndike’s, applied across species lines. “There is a

genetic connection,” Skinner said, “between teaching machines and

Project Pigeon.”

He began work on his teaching machines after sitting in on his

youngest daughter’s fourth-grade arithmetic class. When one of his

pigeons did something right or wrong, it received immediate

feedback. In his daughter’s classroom, however, children filled out

worksheets in class only to receive feedback the following day, when

their teacher handed the graded sheets back to them. Skinner’s

research suggested that this was too late, and so he began work on a

machine\*2 capable of providing instant feedback, which enjoyed

nearly a decade of reasonably widespread use before it became a

cautionary tale, relegated to university storerooms.

In a sense, however, Skinner had been right about one thing: The

behaviorist revolution that Thorndike helped kick off hadn’t fully

penetrated the workings of the classroom itself, or the inviolable

relationship between teacher and student, or students’ innermost

thoughts. Rather, like a pigeon-containing missile, Thorndike’s

legacy, in the form of standardized educational structures,

surrounded these things on all sides.

THORNDIKE GOES TO SCHOOL

In 1900, more than a decade before Watson coined the word

behaviorism and several years before Skinner’s birth, Thorndike

accepted a professorship at Columbia University’s Teachers College,

where he turned his attention away from comparative psychology

and toward human education. His Law of Effect provided the

conceptual underpinnings for what would become a decades-long,

nationwide (and ultimately international) push for standardization

across primary and secondary schools, colleges, and universities.

Throughout his long, exceptionally productive career, Thorndike

would remain an enthusiastic participant in this process, lending

intellectual heft to like-minded figures in the realms of science,

education, and government, known collectively to education

historians as the administrative progressives. As they made their

stamp on mass education, the Law of Effect would both inform their

decisions and, just as frequently, provide their maneuvers with ex

post facto justification.

The administrative progressives were part of a far larger social

trend, known as the Progressive movement, in which institutional

actors sought to impose order on a society that seemed to be going

off the rails. The apparent chaos manifested in a variety of ways,

including urban migration, recessions, the new economic concept of

“unemployment,” and the concomitant rise of both the modern

corporation and organized labor—forces that came into sometimes-

bloody conflict. Of particular interest to educators was the

disappearance of once-reliable escalators to middle-class prosperity,

caused by both the advent of corporations and the national market

economy. Though you might be middle class, the working world

would make no such guarantees for your children.

It was, in retrospect, inevitable that educators would get involved

in trying to fix things; even today, education presents a tempting,

unitary point of influence over a whole host of social problems, with

potential downstream effects touching everything from childhood

poverty to economic malaise to racial inequity, not to mention

existential concerns like falling behind rival countries

technologically. The administrative progressives harbored no doubt

about the seriousness of the problems they were facing, nor that

they were the right people to do something about it.

In theory, that “something” could have resembled the holistic

approach to education Dewey had tried out in his Laboratory

School. Practically speaking, however, it’s hard to imagine the gear

teeth of the larger Progressive movement meshing with any

approach other than Thorndike’s, with its insistence on making

learning measurable, countable, and mass-replicable. As the

education historian Stephen Tomlinson has written, Thorndike’s

views provided the administrative progressives with “the tools

necessary to atomise, sequence and monitor every aspect of

schooling.”

Dewey’s influence would live on, mainly in teacher-education

programs, which would provide a long-standing back channel into

classrooms. But front offices—from individual schools on up to

entire departments of education—would fall in love, and in line,

with Thorndike. His Law of Effect would justify the standardization

of curricula, the standardization of school administration, and, most

disastrously, the standardization of students.

—

Perhaps the first casualty of Thorndike’s theory of learning was the

traditional, classical humanist curriculum. The old idea that skills

bled across categories—that if you honed your “faculty” of memory

on Greek poetry, say, you could later bring it to bear in your career

as an accountant—made no sense in a model where information was

stored in minute, stand-alone associations. And if “faculties” like

memory, reason, perception, and judgment weren’t improvable

(Thorndike experimentally attacked the faculty of “judgment” with

particular zeal), the logical move for school administrators was to

cater directly to students’ future endeavors. The four curricular

pillars of mathematics, science, English, and history survived this

shift unbroken but not unbent. Old standbys such as physics and

trigonometry gave way to “general science” and “general

mathematics” courses meant to apply straightforwardly to “the

home, the farm, the nearby factory, the municipal and water plants,”

as a 1920 National Education Association report put it. History,

reformulated as “social studies,” took on responsibility for churning

out good citizens. Classical languages fell by the wayside in favor of

such inventions as “home economics” and “physical education,” as

well as vocational training in fields like industrial drawing and

woodworking.

By the 1910s and 1920s, a growing set of administrative

superstructures were enforcing these sorts of new norms—to

Thorndike, a strong step in the right direction. He contemplated a

world where teachers would cede entire control of the educational

machine to administrators and curriculum creators (Thorndike,

who made a fortune producing textbooks and dictionaries, being a

standout example). He even anticipated a far-flung future where a

hypothetical algorithm could take the yoke out of teachers’ hands

entirely, anticipating “the effect of every possible stimulus and the

cause of every possible response in every possible human being,” he

wrote in 1906. Whether it was administrators or scientists or

machines delivering edicts from on high, his plans left teachers with

a limited role, lower in the hierarchy. As Ellen Condliffe Lagemann

has pointed out, gender was a major component of this teacher-

diminishing worldview: administrators were often men and

teachers women.

Such ideas couldn’t have resonated more perfectly with the tenor

of the time. A national vogue for efficiency and quantification was

in full swing, and bespectacled, waste-hunting men bearing

stopwatches and notebooks had become a common sight in offices

and factories. In schools, too, pressure mounted to be efficient with

time and taxpayer money. Larger school districts gobbled up their

neighbors while professionally trained administrators, many hailing

from Columbia’s Teachers College, gently coaxed the reins of day-

to-day operations from the hands of local school boards.

To this new administrative class, familiar tools like “credits” and

“credit hours” became indispensable: common coins of educational

attainment not only proffered by students moving within and

between institutions, but also invoked on education’s supply side in

matters ranging from scheduling to teacher pensions to facilities

construction. The standardization of educational time was essential

to the administrative progressives’ larger project. Unfortunately, as

I explore in the chapters ahead, it came at a real cost to the

biological imperatives of learning in the brain.

As Thorndike and his allies gathered influence, however, any

natural obstacles to learning that their system might impose

became less of a concern. In fact, learning itself was losing its

totemic significance at school in favor of another function: sorting

worthy students from unworthy. “Grammar school, high school, and

college all eliminate certain sorts of minds,” Thorndike wrote in

1901, a winnowing process that he embraced as a feature, not a

drawback, of a successful education system. To him, the main

challenge facing schools was not to improve intelligence, but to

separate the apt from the inept. This was the only way to give the

subset of students “who most deserve education beyond a common

school course,” he wrote in 1906, “such a training as will make them

contribute most to the true happiness of the world.”

Later, in 1924, he drove this idea home with a highly influential

study, nominally an investigation into whether newfangled school

subjects or their time-honored predecessors more effectively raised

students’ intelligence. The answer, Thorndike announced, was

“none of the above”; what mattered more than courses studied was

the mental equipment of the students doing the studying. “Those

who have the most to begin with gain the most,” he declared, a

finding that lent urgency to the administrative progressives’

commitment to sorting students. Looking back on the study today,

as the education historian Herbert M. Kliebard has written, “there

may be some question as to whether Thorndike was warranted in

drawing such sweeping conclusions.” In a very real sense, however,

Thorndike’s conclusions were foregone, having been formed

decades earlier.

In the early 1900s, he and other educational psychologists had

endorsed the use of subject-specific standardized tests to compare

students, which public schools readily adopted. (Thorndike didn’t

invent the idea of standardized tests, but he did personally come up

with a number of them, including scales for the comparison of

children’s skills in spelling, handwriting, history, English

comprehension, and drawing.) These were soon overtaken,

however, by the one mental evaluation to rule them all: the IQ test,

which Thorndike embraced wholeheartedly. Although he and the IQ

test’s primary mover, Stanford’s Lewis Terman, disagreed slightly

about what intelligence was, exactly, they agreed that for all

practical purposes it was determined at birth, and IQ did a decent

job of approximating it. They joined forces with other like-minded

educationalists and psychologists and pushed to make IQ testing

the scholastic norm.

As IQ’s influence grew in schools, debates about its efficacy

became heated. Dewey, for one, sided with the opposition, arguing

against any “procedure which under the title of science sinks the

individual in a numerical class…and thereby does whatever

education can do to perpetuate the present order.” Despite such

admonitions, IQ testing became the standard means of student-

sorting in Jazz Age schools and a major preoccupation of the

psychology research community at large. Terman became the

president of the American Psychological Association in 1922. In

1925, the U.S. Bureau of Education determined that 64 percent of

elementary schools, 56 percent of junior high schools, and

40 percent of high schools were using intelligence tests to classify

their students into tracks aimed at either college or blue-collar

work. And, as the education historian and analyst Diane Ravitch has

written, the decision to plop a student onto this track or that

“became a self-fulfilling prophecy, since only those in the college

track took the courses that would prepare them for college.”

—

To what end, all this quantification, this categorization, this

winnowing on a mass scale? The effects, as I’ve mentioned, weren’t

all harmful; even the crudest standardized measures of student

aptitude will result in fairer outcomes than admissions based solely

on who-knows-which-alumnus. And yet, at the same time, whom

did these supposedly meritocratic innovations weed out?

Let’s start with what might by now be obvious. The entire

intelligence-testing project of the early twentieth century was racist

and classist—not just in execution, but also in motivation. The

impulse to weigh and rank students, part of the general Progressive

vogue for quantifying everything under the sun, was also tied more

directly to another movement having a moment in the early

twentieth century: the abhorrent, so-called science of eugenics.

In fact, both threads—behavioral statistics and eugenics—trace

back to a single person, the British polymath Francis Galton, who

can fairly be called the father of both. (He even coined the term

eugenics.) Administrative progressives, especially Terman and

Thorndike, venerated Galton; looking back in a brief 1936

autobiography, Thorndike declared that, together with those of

William James, the writings of “Galton have influenced me most.”

In addition to endorsing Galton’s eugenics notions outright, both

Terman and Thorndike also permitted a deeply unfortunate

combination of racial bias and genetic determinism to influence

their educational outlook. Terman, a particularly virulent eugenics

advocate, was convinced that testing the intelligence of different

races would reveal discrepancies so vast they could never be

resolved by any educational intervention. And Thorndike, who

belonged to New York’s pro-eugenics Galton Society, endorsed a

combination of segregationism and vocationalism: for instance,

changing “certain schools for Negroes from a predominantly literary

to a predominantly realistic and industrial curriculum.” Even as late

as 1940, when anthropologists had revealed that there was far more

to human nature than what was written in our genes (while

geneticists, wielding new chromosomal research findings, had

demonstrated that there was far more going on in our genes than

eugenicists understood), Thorndike still endorsed eugenics. “One

sure service of the able and good is to beget and rear offspring,” he

wrote. “One sure service (about the only one) which the inferior and

vicious can perform is to prevent their genes from survival.”

Today, there is no shortage of research disputing the

assumptions underlying Thorndike’s and Terman’s racial theorizing.

In fact, as I’ve already mentioned, environmental factors have an

enormous effect on performance on even modern IQ tests—

sufficient, in the cases of underserved races in the United States, to

more than eclipse any hypothesized group differences. What’s more,

marginalized populations around the world, as the anthropologist

John Ogbu has written, tend to score ten to fifteen IQ points below

local dominant groups. These differences disappear when both

groups migrate to a new setting, the only plausible explanation for

which boils down not to genetics but rather to the experience of

marginalization. Or, as Vox’s Ezra Klein has put it concerning the

United States in particular, the real issue isn’t “that IQ isn’t

heritable, or even that it’s impossible to imagine it differing among

groups. It’s that it’s impossible to look at the cruel and insane

experiment America has run on its black residents and say anything

useful about genetic differences in intelligence.”

—

Thorndike, the scientist who more than anyone brought the study of

learning into the quantitative era, built a reputation as a

dispassionate logician—especially when compared to the more

anthropological and introspective Dewey. With all his ideological

background details filled in, however, Thorndike begins to look less

serenely rational and more like any other hot-blooded human,

complete with an all-too-human tendency toward motivated

reasoning and confirmation bias. He and his fellow administrative

progressives permitted just-so stories about race and intelligence to

interfere with their ability to abstract truths from the world around

them. (Their willingness to entertain myths wasn’t limited to

intelligence, either. Thorndike used an index of class and race to

draw an American map of purported “goodness.”) You could be

forgiven for laughing at this sort of scientific hubris—until you

remembered the serious harm such hubris visited upon the world.

We’re still living with the legacy of the Progressive Era’s bunk

science. To this very day, our systems of education are charged with

a dual set of goals that sit in uneasy coexistence. On one hand, the

primary goal of mass education is still to teach: to confer useful,

activated knowledge on everyone. On the other hand, our secondary

mission, inherited from the administrative progressives, tells us to

standardize education’s content, delivery, and even its recipients—

which often runs counter to the ideal of learning for all.

This low-simmering state of dissonance runs hot wherever the

machinery of standardization clashes against the reality of how

learning actually works. As I’ve mentioned, the cognitive science of

learning is a multilayered affair, comprising far more complexity

than Thorndike’s base-level theories account for. In the chapters

ahead, we’ll climb up through the layers of this cognitive high-rise,

with each level expanding our scope. We’ll begin at the microscopic

scale—how does learning register in the very cells that compose our

nervous system?—and ascend until we reach rarefied levels

encompassing metacognition (how we think about thinking) and

social dynamics. Each layer imposes new conditions on learning;

addressing these conditions may lead us to a more inclusive,

effective vision of education for educators and learners alike.

I hope it’s clear by now that I hold Thorndike’s legacy in mixed

regard at best. And yet as we move forward, we must reckon with

the uncomfortable fact that (at least in terms of methodology, if not

ideology) our coming voyage will have undeniable Thorndikean

aspects. True, we’re adding layers to something he saw as two-

dimensional, but still, we’ll be seeking to understand learning by

breaking it down into its nuts and bolts—an underlying impulse he

would have recognized immediately. Thorndike’s reductionism was

an extreme form of an approach I’ll refer to as inside-out thinking:

attempting to explain complex systems as mechanistically as

possible. Inside-out thinking offers a powerful way to abstract

truths about the world, and an even more potent way to engineer

theory back into practice. That is, assuming the model you develop

is faithful to reality, which, in Thorndike’s case, wasn’t quite true.

Dewey’s more holistic ethos, meanwhile, is an example of what

I’ll refer to as outside-in thinking: experimenting on a complex

system as a whole, without cracking it open. This relatively cautious

approach is less susceptible to ruinous error, but is also

substantially harder to convert into educational practice at scale.

It’s clear to me that any truly ambitious attempt to propagate

learning of the caliber I’ve witnessed in 2.007 will require both

inside-out and outside-in thinking. Together, these seemingly

contradictory impulses may enable a more intentional approach to

education, where we break with the past as necessary, but without

jettisoning the secret sauce of the classroom altogether, as in

Skinner’s teaching machines. The next two chapters, dealing with

the lower, more fine-grained levels of the cognitive high-rise, will

necessarily reflect an inside-out ethos. Then, as we climb higher,

we’ll begin to stray into the realm of outside-in research. As we’ll

see, these two strands of scientific thought can lead to wildly

different recommendations for educators, ideas we’ll have to

reconcile if we hope to offer a clear vision for how best to nurture

learning.

For our first chance to challenge the status quo, however, we

won’t need to climb far at all. In the next chapter, I’ll describe how,

even at the fundamental level where Thorndike’s theories still hold

the most water, the biological reality of learning intrudes, and hints

at a better way.

\*1 And there are students who fit this profile at MIT—they just tend to do the bare

minimum needed to earn an A, as opposed to a B. I recognize the type; I used to be one.

\*2 Strictly speaking, a handful of teaching machines and related patents predate Skinner’s—

most notably, the machine developed by Sidney Pressey, a Jazz Age psychologist

influenced by Watson and Thorndike. His invention, an intelligence-testing machine that

also happened to correct wrong responses, only ever sold 127 units, however, perhaps

because it was expensive and the Great Depression was unfolding.

- II -

LAYER ONE: SLUG CELLS AND

SCHOOL BELLS

“Space out your studies!”

“Don’t cram for exams!”

“Start studying before the night before!”

I don’t know if there is any truly universal experience in this

vast, variegated world, but hearing the above injunctions must come

close. How many of us, over the decades, have been told that it’s a

bad idea to limit our studies to the night before a test? That it’s a

hallmark of laziness, of poor time management, moral decrepitude?

That, down the road, it leads to poor retention, diminished

prospects, occasional dyspepsia, sweaty palms, epidemic

unhappiness?

And yet, despite the direness of these warnings, many of us

persist in making the wrong choice. I know I did, well into

adulthood. So do many of my students, despite the fact that I’m now

the one urging them to space out their studies. And so do students

everywhere. In one study from 2013, half of the college-age students

surveyed said they commenced studying only a day or two prior to

their exams (and, bear in mind, these are the students who

admitted it), despite the fact that the vast majority said they knew

better.

Indeed, study sessions separated by days, even weeks, are

dramatically more effective than studying all at once. Spaced

learning, alternately referred to as “spaced repetition” and “spaced

practice,” is up there with vigorous daily exercise and flossing in the

universally-acclaimed-yet-avoided department. If its benefits came

in pill form, as they say about exercise, we’d all take it every day.

The spacing effect is one of the longest-researched topics in

cognitive psychology, and a wide variety of experiments, ranging

back to the German psychologist Hermann Ebbinghaus’s studies of

his own recall in 1885, have shown it to work for all sorts of

knowledge, in all sorts of students.

Want to learn Swahili? When researchers broke a vocabulary

study session into two sessions separated by a one-day gap, students

remembered 34 percent more Swahili words come test day, a week

and a half later. Want to learn math? Four weeks after their lessons

ceased, college students who practiced problems in spaced

installments performed twice as well as those whose studies were

lumped into one long session. Researchers have observed similar

results among science students, too. Spacing has been shown to

work in adults as old as seventy-six as well as in children, and even

infants—and not just in academic realms of knowledge either, but

also in unplanned-for, incidental learning, and even for motor skills,

redounding to the benefit of everyone from expert pianists to novice

golfers learning to putt. It also works in areas where bookish

knowledge and motor skills intersect, such as the surgical operating

theater. In one 2006 study, surgeons learning to interconnect rats’

blood vessels who were taught in sessions spaced out over weeks

performed significantly better than a control group given massed

practice (that is, the opposite of spacing). In fact, only in the massed

practice group did some surgeons make such a hash of their work

that they had to give up on their tiny patients.

Wide-ranging though the above examples may seem, they

account for a vanishingly small segment of the spacing effect’s true

sphere of influence, which runs much, much further afield than the

human species. Our fellow mammals, too, seem to benefit from

spacing, which might not come as a shock—they are, after all, our

close relatives. Perhaps more surprisingly, however, relatively

simple invertebrates also profit from a little space in their

education. Fruit flies can be taught to fear certain odors, for

instance, and this memory proves stickier if their training sessions

are distributed. But still, fruit flies at least have a brain.

Astoundingly, even animals without a brain or central nervous

system can still benefit from spaced repetition. Take the sea slug

Aplysia: a graceful, squishy genus, typically the size, shape, and

color of a well-done pork chop. It has no central nervous system to

speak of, and relies instead on a distributed net of neurons. Even

these seemingly unsophisticated animals, when taught to react to

different experimental stimuli, can remember what they’ve been

taught for longer when that instruction is spaced out.

And Aplysia really is a simple species, neurologically speaking.

The human brain contains 86 billion neurons. Aplysia, brainless—

yet, one imagines, content, as it goes about its day grazing on

marine algae—boasts just 18,000 neurons in its decentralized

network. If you wanted to hand out a human brain neuron by

neuron, you could give one to each resident of twelve consecutive

Earths. By contrast, you could hand out Aplysia’s neurons as a

participation prize at the Boston Marathon and still leave ten

thousand finishers disappointed.

If having a neuron count just one five-millionth of ours doesn’t

stop Aplysia (and even simpler animals, for that matter) from

benefiting from spaced learning, that means something. The fact

that the benefits of spacing are so resoundingly conserved all the

way out to the farthest reaches of the animal kingdom suggests that

there is something essential about spacing. Long treated as a

peripheral concern by educators—a good habit to promote, but not

something to get worked up over—spacing in fact deserves more of a

starring role in how we think about teaching and learning. As a

cresting wave of research is now suggesting, it appears to be crucial

to the very mechanisms that make memory possible.

CAJAL’S PROPHECY

The spacing effect wasn’t always given short shrift in memory

research. To Hermann Ebbinghaus, the bearded, bespectacled

German researcher who helped found the field, it was the key to

making memories stick. In a series of meticulous experiments he

conducted on himself by memorizing long sequences of nonsense

syllables, Ebbinghaus quantified forgetfulness over time, describing

a “forgetting curve” in which most of the syllables faded quickly

from memory, but a few lingered far longer. Repetition, he

observed, could steel-plate memories for the long haul, especially if

spaced out over time. This finding made a certain amount of

intuitive sense: After all, he reasoned, “the schoolboy doesn’t force

himself to learn his vocabularies and rules altogether at night, but

knows that he must impress them again in the morning.” In 1890,

upon reviewing Ebbinghaus’s research, William James proposed the

existence of two separate categories of memory, which he called

“primary” and “secondary.” It was probably his student, the prolific

E. L. Thorndike, who, in 1910, gave them the names most people

would recognize today: short-term and long-term memory.

In the years that followed, psychological research into spacing

didn’t grind to a complete halt, but it didn’t exactly set the eyes of

leading memory researchers alight with passion either. To the

behaviorists and their progenitors like Thorndike, spaced repetition

seemed helpful but far from essential, providing a useful schedule

over which to train rats, pigeons, and pianists, but little else. And so,

as psychologists toiled to catalogue which stimuli led to which

behavioral outcomes, spacing took on sideshow status.

The behaviorist-allied psychologists weren’t the only scientists

plumbing the depths of memory at the time, however. While

Thorndike and his heirs did their best to understand learning from

outside the skull, neurophysiologists were already poking around

within. Soon enough, the physiological brain, so long a mystery

wrapped in fascia, bone, and skin, began grudgingly to give up its

secrets. By necessity, however, these early efforts were concerned

with gaining the lay of the brain’s terrain: what neurons looked like,

how and when they seemed to convey information, how they

connected to each other. With these sorts of questions still looming,

the how and why of spacing would have to remain unanswered.

A separate question, just as intriguing but no less remote, was

when the paths of memory research in psychology and physiology

would meet. The behaviorists, to their credit, never doubted that at

some far-off point, the corporeal structures underlying learned

behavior would eventually come to light. Skinner, squinting at the

hazy future, predicted, “What an organism does will eventually be

seen to be due to what it is, at the moment it behaves, and the

physiologist will someday give us all the details.”

To midcentury neurophysiologists, meanwhile, the physical stuff

of memory actually felt closer at hand—albeit wraithlike in its

ability to avoid detection. Their research tradition began with

Santiago Ramón y Cajal, the Nobel Prize–winning Spanish

neuroanatomist whose painstaking drawings of branching, forking

neurons remain in educational use to this day. In an 1894 lecture

delivered in French to a group of London scientists, Cajal issued a

prediction: Memory was made possible by the formation of novel

connections—later named synapses—between neurons. “The

cerebral cortex is similar to a garden filled with trees, the pyramidal

cells,\*1 which, thanks to an intelligent culture, can multiply their

branches, sending their roots deeper and producing more and more

varied and exquisite flowers and fruits,” he told his rapt audience.

He was on the right track. In fact, if a neuroscientist today went

back to 1894, sloshed Cajal on the back of the head with a blackjack,

and delivered his lecture in his stead, that time traveler’s message

would differ in only a few key points. But Cajal’s new-connection

theory was untestable at the turn of the century, and in the

meantime, other, competing explanations seemed just as likely. In

the 1920s, for instance, based on the maze-navigating skills of rats

missing chunks of their brains, the Harvard psychologist Karl

Lashley supposed that memories were preserved by electric fields.

In 1949, Lashley’s onetime student, Donald O. Hebb of McGill

University, put forward a theory, more closely aligned with Cajal’s,

that turned out to be significantly warmer. The big problem, then as

now, was one of complexity. In today’s textbooks, neurons tend to

be drawn simply, for ease of comprehension. As traditionally

depicted, a neuron looks sort of like a tulip plant that’s been plucked

from the ground, root bulb and all, and laid end-to-end with similar

plants in front and behind. At one end, emanating from our plant’s

bulb, a number of root-resembling structures called dendrites

receive incoming signals from prior neurons. Once a signal is

received by a dendrite, it travels the length of the neuron: past the

bulb-shaped cell body, which contains the nucleus and other life-

support systems; and along the narrow, lengthy stem, known as the

axon. This transit occurs by way of an electrochemical mechanism

known as an action potential (which is frequently analogized, to mix

metaphors, to a line of falling dominoes). When the action potential

reaches the flowery bits, known as axonal projections, these finally

pass the signal along to the next neuron by dumping a payload of a

chemical (a neurotransmitter) into the empty space (a synapse)

separating the petals of our neuron from the roots of the next. And

so the signal continues ever onward: excelsior.

There actually are neurons in the body that look and act almost

as simplistically as this textbook ideal: simple messengers that do

little more than convey a signal from point A to point B. But in the

brain, things are not drawn so clearly. A given cortical neuron is

connected not at two points, fore and aft, but at on the order of ten

thousand synapses (and sometimes as many as a hundred

thousand), which connect it to many thousands of other cells. One

of the toughest problems midcentury neuroscientists faced,

therefore, was the question of when such a cell—not a tulip in an

orderly row so much as a thorny shrub in the densest underbrush

imaginable—receives an incoming signal, under what circumstances

does it deign to pass said signal along? And, when it does, which of

its many, many downstream neighbors receives the message?

Hebb suggested that every time one neuron causes another

neuron to fire in a chain reaction, some self-reinforcing process

must happen in those cells (and their shared synapse or synapses)

to make that reaction increasingly likely to recur. The upshot was

the existence of orderly, semi-discrete assemblies of brain cells,

formed and maintained through the repeated usage of particular

synapses. Or, as neuroscientists like to say today: “Neurons that fire

together, wire together.” The idea was revelatory.

More intriguing, however, was Hebb’s corollary: Perhaps it was

these web-like assemblages of cells that preserved memories in the

warp and weft of their connections. As results piled up in support of

Hebb’s theory, neuroscientists began to circle. If the site of

memory could be located physiologically, then it was just a question

of how, by whom, and in what model organism: cat or rat, mouse or

monkey.

ENTER APLYSIA

Or—though very few experts of Hebb’s era would have predicted it—

the sea slug Aplysia, known mainly for the simplicity of its nervous

system. Behaviorism-inclined researchers approaching memory

preferred complex animals: mammals and certain birds capable of

impressive feats of problem solving and memory. Meanwhile, to the

neuroscientists working in relatively simple animal models,\*2

behavior was the hang-up. When you were peering through a

stereoscope and dissecting out individual neurons, an animal’s

rationale for climbing a tree, grooming a mate, pushing a lever—that

was all unassailably complex. As Eric Kandel, the neuroscientist

who eventually earned a Nobel Prize for describing the connection

between memory and the action of individual neurons, recounted

over the phone in 2018: Most researchers “shied away from

behavior. They thought it was too messy and too complicated.”

Kandel was born in Vienna, Austria, but he and his family fled

the Nazis in 1939, when he was nine years old, alighting in

Brooklyn. By the mid-1960s, Kandel, who trained as a medical

doctor before turning fully to research, had experienced

neuroscience at the level of both entire brains and individual cells.

After a maddening early experience at Columbia University studying

the hallucinogenic effects of LSD, not yet a restricted drug, on the

highly complex visual cortex of cats, Kandel yearned for a simpler

study subject. He soon found himself drawn to the laboratory of a

neighboring researcher who was probing the properties of crayfish

neurons. There, he learned to manufacture glass electrodes, insert

them into the crayfish’s large axon—not quite the size of the squid

giant axon, but substantial nonetheless—and connect them to a

loudspeaker. The setup transformed silent neural activity into an

audible cannonade. “I am not fond of the sound of gunshots,”

Kandel wrote in his memoir, In Search of Memory, “but I found the

bang! bang! bang! of action potentials intoxicating.”

A few years later, working again with cats, Kandel had

the opportunity to use these electrode techniques in the

hippocampus, the brain region that had recently been shown to be

essential to long-term memory formation thanks to a series of

landmark studies by McGill’s Brenda Milner.\*3 Since hippocampal

neurons were required for long-term memory formation, Kandel’s

plan was essentially to poke around and see what made them so

special. In short order, he and his research partner made a number

of minor discoveries, but perhaps their most important insight came

from the absence of a major breakthrough. The hippocampal

neurons they were studying were special, it seemed, but not special

enough to account for the hippocampus’s unique role in memory.

That suggested an intriguing possibility: The stuff of memory might

not reside within cells so much as between them.

Against the advice of senior colleagues, Kandel swung his sights

back to simple invertebrates. As he later wrote: “Few self-respecting

neurophysiologists, I was told, would leave the study of learning in

mammals to work on an invertebrate. Was I compromising my

career?” But Kandel knew what he wanted: a study system that

could do for memory what the squid giant axon had done for the

action potential. Something, perhaps, like a certain sea slug Kandel

had encountered in a pair of lectures by visiting scientists. “The

advantage of Aplysia was, the nerve cells are gigantic. They are

uniquely identifiable. And you could work out a simple behavior in

terms of the neural circuit,” he recounted. “If you know the neural

circuit, you can see what happens to the neural circuit when the

animal learns something.”

The way he described it in retrospect, “see what happens to the

neural circuit,” sounded almost straightforward. At the time,

however, it was tantamount to the holy grail of memory research,

because if you could describe what happened to every cell in a

circuit where learning had occurred, you might just have a cellular

explanation for memory.

—

Before he could join the French laboratory of Ladislav Tauc, one of

the visiting Aplysia researchers, Kandel had to complete a two-year

medical residency at Harvard Medical School, to which he had

already committed. Residency was a more humane affair in the

1950s, however, and Kandel found it gave him time to read books,

including B. F. Skinner’s The Behavior of Organisms, which spelled

out a number of Pavlov’s and Thorndike’s classic study protocols. “It

occurred to me that the paradigms they described,” Kandel later

wrote, “could readily be adapted to experiments with an isolated

Aplysia ganglion.” With any luck, the type of inside-out learning

model proffered by Thorndike and Skinner might even meet its

long-dreamt-of biological mechanism.

After two years, Kandel and his young family made the trip to

join Tauc in the seaside town of Arcachon. Finally, having stepped

away for so long from the simplified neurological world of lobsters,

crayfish, and squids, Kandel had returned—to reductionist, inside-

out science; to the continent of his birth; to les fruits de mer.

SLUGGISH WORK

A little more about the magnificent creature that is Aplysia. Its

enormous axons—the anatomical oddity that first caught Kandel’s

eye—are slightly wider than the Humboldt squid’s giant axon,

especially remarkable in an animal you can hold in your hand, as

opposed to one you could hold only in a wet bear hug. When

threatened, Aplysia can squirt ink with the best of them. They are

also hermaphrodites, and form mating chains of as many as thirty

individuals, with the slug at the back acting as a male, the one at the

front as a female, and everyone in between pulling double duty.

Sometimes, the locomotive meets the caboose, creating a pulsating,

slimy ouroboros. Aplysia also exhibit an easily identifiable response

to abject terror. In the wild, its spongy gill-and-siphon apparatus is

exposed to the watery world most of the time, sticking out of its

back like a backpack. Because the gill is both delicate and, to

predators, delicious, whenever there’s a hint of a threat nearby,

Aplysia protects its gill by pulling it inward, into its body. Perhaps

most important, this reflex can be trained—a fact Kandel would use

to his advantage.

First, however, before working with the whole animal, Kandel

focused in on Aplysia’s neurons. He removed an abdominal cluster

of two thousand nerve cells, and, keeping them alive in aerated

seawater, he sank electrodes into the biggest neuron he could find.

He then stimulated smaller neurons converging onto the big one in

an attempt, using just raw nerves and electrical signals, to replicate

some of the most famous learning experiments from the history of

the behaviorists.

There are three super-simple forms of learning, all of which were

observed by the Russian proto-behaviorist Ivan Pavlov in his

groundbreaking studies on dogs, which he conducted mainly by

measuring their saliva production before and after various training

regimes. The first, habituation, is a reaction to a constant neutral

stimulus: for instance, when you move to a house near a rushing

stream and gradually cease to register the sound of the water. The

second, sensitization, is a response to an intermittent, usually

noxious stimulus: when some unidentifiable device in your house

emits an ear-splitting beep every fifteen minutes, causing you to

jump higher each time. The third, known as classical conditioning,

happens when a significant stimulus—something causing

discomfort, fear, sexual arousal, etc.—becomes paired with a neutral

stimulus. For an unsettling example, recall poor Little Albert, the

toddler John Watson trained to fear fuzzy things.

Kandel achieved a habituation-like reaction first, by repeatedly

triggering an incoming neuron to fire, which led to diminished

responsiveness of the gigantic cell downstream. If an action

potential is like a line of falling dominoes, the electrical value

Kandel was measuring in the downstream cell, called the synaptic

potential, is like the first domino’s angle of tilt: push it beyond a

certain threshold point and watch them all fall over. Using this

metric, you can infer a synapse’s strength; essentially, the more an

upstream signal causes the downstream “domino” to “lean,” the

stronger your synapse. Kandel discovered that under his simulated

habituation, the synapse in question had weakened significantly, as

expected.

Successful simulations of sensitization and classical

conditioning soon followed. Kandel was now tantalizingly close to

describing the cellular basis of real memories: reducing learned

behaviors of the sort Pavlov had observed in living, breathing dogs

down to the activity of individual synapses. This principle, however,

could only be proven in living, behaving sea slugs, as opposed to the

cell clusters Kandel had been working with—and in the meantime,

his time in France was growing short. Upon returning to New York,

Kandel assembled a crew dedicated to divining Aplysia’s remaining

secrets. The team settled on the gill-withdrawal reflex as their

primary study target, and Kandel used electrodes to painstakingly

map out the neurons involved, which, he was pleased to discover,

didn’t vary from slug to slug. The real trick, however, was gathering

readings of neural responses from live slugs, which Kandel and

company eventually achieved by anesthetizing one, opening its

neck, and pulling a still-connected abdominal ganglion out onto an

operating stage. By 1969, the team had worked out how to measure

the synaptic potential of the six motor neurons directly responsible

for gill withdrawal. They began to train their slugs, electrodes at the

ready.

And just like that, the dam broke. Sensitization and habituation,

visible in the slug’s gill-withdrawal behaviors, matched perfectly

with the strengthening and weakening of the gill-withdrawal

synapses. Classical conditioning proved tougher to crack, but the

team eventually turned in similar results, showing that when they

trained Aplysia to respond fearfully to a benign stimulus, it formed

a chain of strengthened connections between sensory cells and

motor neurons that had previously had nothing to do with one

another.

In light of these stunning inside-out findings, long-simmering

controversies began to fade. Lashley’s electrical field theory of

memory no longer made sense. Meanwhile, the far more esoteric

argument over whether the human mind starts out as a blank slate,

a position associated with the British philosopher John Locke, or

comes partially preprogrammed, as the German rationalist

Immanuel Kant advocated, became somewhat moot. If Aplysia’s

neural setup and our own brains had anything in common,

preprogrammed information did indeed come stamped into the

anatomy of neural circuits, per Kant, while individual experiences,

in accordance with Locke, determined how and when those neural

circuits passed along signals. “The potential for many of an

organism’s behaviors is built into the brain,” Kandel wrote.

“However, a creature’s environment and learning alter the

effectiveness of the preexisting pathways.”

REMEMBRANCE OF THINGS PAST

Perhaps the most important implication of Kandel’s findings was

that there was now a viable cellular mechanism for learning by

association, the mechanism underlying E. L. Thorndike’s theory of

mind. In Kandel’s experiments, however, the phenomena being

associated were limited to simple stimuli and responses. How, you

might reasonably wonder, can a system consisting of strengthened

or weakened connections represent ideas? It’s easy enough to

imagine how someone might, say, sit on a cactus once or twice and

develop an aversion to the sight of succulents. But how can such a

system represent the idea of what a cactus is?

To explain, let’s switch over from sight to smell, since visual

signals undergo a great deal of processing on their way into the

brain, while odor signals slip in with less modification. For a nose-

wrinkling example, take the smell of an overripe banana. Let’s

suppose that you first experienced that unforgettable smell

relatively recently—say, just one year ago. How, according to

Kandel’s model, could that smell have become represented in your

memory?

When you first smelled that squishy, brown banana, a bouquet

of volatile chemicals entered your nose and fit, lock-and-key-style,

into some subset of your five or six million odor receptor cells,

which come in some four hundred varieties. Those receptors that

happened to match up with the volatile banana chemicals each fired

off a series of action potentials that proceeded straight upwards,

through perforations in the thin sheet of bone separating your nasal

cavity from your brain, into the brain region sitting just on top of it,

known as the olfactory bulb.

There, those incoming action potentials could have either

triggered a second round of action potentials, leading further into

the brain, or not.\*4 Let’s assume the former: The thousands of

signals entering this first relay converged on a much smaller set of

cell clusters, which reduced the cacophony of incoming signals to a

relatively organized symphony before passing them along.

Here’s where things got interesting. Eventually, the incoming

odor signal reached a group of interconnected neurons that

somehow penetrated into your conscious awareness when they

fired. We don’t know how activated cell assemblies trip into

conscious awareness. (In fact, cognitive scientists disagree about

whether we’re even close to answering that question.) However, we

do know that when groups of cells in certain areas of the brain light

up with activity, sensations, ideas, and yes, memories, tend to fill

our thoughts. In the case of our banana, when that assembly lit up

for the first time, you experienced a new sensation, with some

preprogrammed reactions mixed in. The sweet component of the

smell, for instance, might have made you salivate.

If you were a simple animal like an Aplysia, the show would be

almost over: You would act (eat the banana, run away from the

banana), possibly develop some aversion or attraction toward future

banana smells, and that would be that.

But you are most likely not a simple animal. In fact, you possess

a brain that can be fairly considered the most complex stand-alone

object in the known universe. And so when the banana smell came

flooding in and started lighting up neurons, you didn’t just act on it.

You also created an internal representation of that smell in your

head for future reference. Which meant that in addition to the

nervous action going on at the ground floor of your brain, there was

another assembly of cells lighting up somewhere upstairs.

In this model of memory (owing perhaps to a hypothesized

ability of neurons known as template matching), such assemblies of

cells will fire only if the right combination of incoming signals

reaches it. Those signals can come from the senses—that is, the next

time you encounter a banana—or they come in from the side, via

associated memory assemblies. After just a single banana

encounter, you’ll have associated a number of memories with the

smell, such as the room you were in when you smelled it, who was

with you, and the visual image of the fruit. You can also add

additional associations after the fact. Importantly, a number of

these associated memories will light up the next time you encounter

a banana, and also the next time you simply think of a banana. Over

time, the assemblies representing the smell of a banana, the sight of

a banana, the word banana—these all become interconnected,

essential components of what a banana means to you.

In this model of memory, then, the modulation of synapse

strength of the sort Kandel observed in Aplysia permits an

associative theory of mind recognizably similar to the one

Thorndike postulated at the start of the twentieth century. Indeed,

what made Kandel’s approach so special was not his technical skill

in the neuroscience laboratory so much as his interest in the sorts

of simple learning patterns that had inspired Thorndike. In the

1960s and 1970s, as Kandel later explained over the phone from his

lab at Columbia, he was far from the only neuroscientist able to

place electrodes inside neurons. However, he said, “I was one of the

few people in the world who was able to put an electrode into a

neuron, who was interested in behavior, and wanted to analyze it in

a cellular level.”

“The reductionist approach that Thorndike, Watson, and Skinner

led—that was very good,” Kandel said. “But it doesn’t give you

mechanism. They simplify the behavior, and they show the behavior

is altered. What you can do with biology, with reductionism, is get

the mechanisms, and therefore go deeper into the problem.” When

asked whether the behaviorists oversimplified, Kandel replied in the

negative—their instinct to find inside-out explanations for learning

wasn’t wrong; they were just limited by the tools of early-twentieth-

century psychology. “They just didn’t go far enough,” he said.

SPACING STRIKES BACK

In the list of mysterious phenomena that midcentury psychologists

like Skinner hoped physiologists like Kandel would someday clear

up, the spacing effect never ranked near the top. As the

physiological work progressed, however, it soon became clear that

there would be no explaining the mechanism of synaptic plasticity—

changes in synaptic strength—without also accounting for the role

played by time.

Of particular note was a finding Kandel’s team made in 1971. If

they stimulated Aplysia’s siphon forty times in a row, they

discovered, it would lead to a one-day-long habituation of the gill-

withdrawal reflex. But if they spaced out the protocol over the

course of four days, then the habituation lasted weeks. It was

already well known, going back to Ebbinghaus, that spacing out

one’s information intake had profound implications for the

stickiness of the resulting memory, but no one had ever put a finger

on where this attribute of learning resided biologically. Kandel and

company’s findings suggested its roots were very deep, indeed:

conserved across species, and perhaps even isolable, like memory

storage itself, down to the activity of individual synapses. No longer

a sideshow of little relevance to more pressing neuroscience

questions, spacing appeared to be at the very heart of memory

formation.

But how, exactly, did synaptic strengthening work? A few clues

were known already. In 1963, a team led by the married couple of

Josefa and Louis Flexner had showed that mice, given a drug that

interfered with their cells’ ability to synthesize new proteins, were

able to form new short-lasting, but not long-lasting, memories. This

result hinted at two, maybe more, separate cellular mechanisms

underlying memory: one that neurons could accomplish using just

the molecular tools readily at hand, and one that required the

neuron to fabricate new tools, in the form of proteins, from scratch.

Kandel’s team replicated these findings at the level of individual

Aplysia neurons and then began delving into the molecular

mechanisms involved. The mechanism for short-term memory

storage yielded first. Intuitively enough, it hinged on the amount of

neurotransmitter dumped into a memory synapse by its upstream

neuron: more neurotransmitter, temporarily strong synapse,

temporarily strong memory.

Now the hunt was on to find the “switch” neurons flipped to

make ephemeral memories more enduring. In 1973, a hint arrived

from Norway, where the researchers Timothy Bliss and Terje Lømo

had blasted a neuron in a rabbit’s hippocampus with a high-speed

train of electrical stimuli: one hundred jolts per second. Stunningly,

the resulting boost in synaptic strength stuck around not for

minutes, but for days. Onto this durable form of synaptic

strengthening they bestowed the name long-term potentiation, or

LTP. Like a well-preserved memory, the name stuck, despite the fact

that, as became increasingly clear in the 1990s, LTP was really an

umbrella concept, comprising multiple causal mechanisms and

stages.

Today, LTP isn’t the only candidate for how the human brain

stores its lasting memories, but it’s the clear frontrunner. The end

stage of the process is fully reliant on the synthesis of new protein,

just like long-term memory in lab mice, and now, thanks to

advances in microscopy, we have a decent picture of what at least

some of that protein is up to. LTP, it turns out, sends neurons

through startling structural, anatomical changes. The local synaptic

sites on the downstream neuron, known as spines, can increase in

size markedly, adding neurotransmitter receptors along the way,

which makes for a stronger synapse. Even wilder, whole new spines

can also form, sometimes doubling up on the original upstream

synaptic site, and sometimes forming brand new synapses, the

effect of which may be to reinforce the original neural pathway

multiple times over. Learning, it seems, doesn’t just change your

mind; it changes the literal structure of your brain.

The highly contrived, highly electrified conditions of

experiments like Bliss and Lømo’s don’t occur in the wild, however,

which raises the question of whether LTP really is responsible for

memory, or if it’s more of a laboratory artifact. The indirect

evidence in LTP’s favor includes its temporal milestones; like long-

term memories, LTP is quick to form, long-lasting (persisting for a

year in one study, and it may endure for longer), and its effects can

be impaired in animals that have a diminished ability to learn (such

as rats at the end of their natural lifespan). Meanwhile, when

neuroscientists tailored their LTP induction protocols to mimic

natural patterns of brain activity, it led to stronger synapses than

standard methods—a hint that LTP can occur on its own, without

electrode-toting scientists spurring it on.

LTP can also claim deeper, more mechanistic support. In one

LTP-like mechanism Kandel’s team discovered in Aplysia, a third

neuron intervenes by delivering a trickle of the neurotransmitter

serotonin to the upstream neuron of a memory synapse. This signal,

passed forward by a chain of messenger molecules, snaps the

memory synapse into a state of long-lasting robustness. Assuming

something like this process also applies in our vastly more complex

brains, it may help explain how moments of heightened emotion—

waking up to the sight of a hungry monkey, for instance—can take

on a flashbulb-like quality in retrospect, preserved in vivid detail. (I

remember every tooth in that monkey’s mouth.) In this model, your

heightened emotional state acts as the trigger for the

overriding signaling cascade, telling your memory neurons to retain

incoming sensory information for the long haul.

This flashbulb effect is a useful, if sometimes trauma-preserving,

feature of human memory. And emotion certainly has its place in

education; an especially inspiring lecture, for instance, can stick

with you for a lifetime. More often, however, we learners find

ourselves ingesting facts and ideas without the mnemonic benefits

of emotion. In these more workaday circumstances, learning is still,

of course, possible—and we still likely have LTP to thank. In fact,

perhaps the most important piece of evidence supporting an LTP-

centric model of memory is the fact that, like long-term memory

itself, LTP obeys the spacing effect. In the laboratory, spacing out

LTP induction intensifies its physiological effects on both upstream

and downstream sides of the synapse. Neuroscientists have

proposed a few explanations for how this happens. In one

persuasive hypothesis, only a subset of the molecular machinery

that enables LTP is ready for action at any given time, a setup that

rewards multiple, spaced-out encoding attempts, since each attempt

gives you a fresh chance to recruit newly mature cellular

components. According to this theory, the spacing effect may in fact

be the cause, not the effect, of this cellular state of affairs. If

information encountered repeatedly is more vital to survival than

information encountered only once, then perhaps we animals have

evolved a deep-seated filter to prioritize its storage.

There’s more to learning—far more—than the encoding of

memories at the synaptic level. In the chapters ahead, I’ll talk about

learning strategies arising at different levels in the cognitive high-

rise: this one due to the structure of the brain, that one due to

psychological motivating factors, and so on. What makes the

spacing effect so special, however, is its depth. From the surface

level of cognitive science, where students and psychologists alike

can readily observe it, the spacing effect plunges down, down, down

—to the very stuff of memory itself.

THE LONG WEIGHT

Sometimes, when I ponder my own relationship with learning, and

how spaced repetition figured into it, I think about something called

“the long weight.”

After I graduated from university, having passed my remedial

control theory course by the skin of my teeth (and following a short

but pleasant stint at the University of Hawaii), I was lucky enough

to land a job with Schlumberger, a company that builds and

provides products for oil companies.

A few months later, I found myself strapped into a helicopter

that had just departed Aberdeen, Scotland, clad in an insulated dry

suit the company insisted I wear, ostensibly to give me a fighting

chance in the frigid waters below in the event of a crash. The

chances of something like that happening were remote, and yet I

had to recognize that suddenly, for the first time, the stakes in my

life had become tangible. My years devoted to vague preparation, to

practicing for the real thing, were over. I pictured my helicopter

silhouetted against the sun, like the famous image from Apocalypse

Now. I was coming in to do work. My period of preparation was

complete.

And what a period it had been. Once I’d signed on with

Schlumberger, they’d whisked me off to their training facility in

Edinburgh, where I’d spent the better part of two months preparing

for my job in conditions that can only be described as deliberately

annoying. An oil platform, as my fellow trainees and I were told, is a

miniature, floating city designed for one purpose: to stab a glorified

drinking straw through three hundred feet of moving water and a

mile of earth and pull out a pressurized, explosive substance.

Problems in such a system never stop arising, and our job would be

to fix them—and on the problem’s schedule, not our own. Which all

sounded perfectly acceptable, until I discovered that our onshore

training schedule would be every bit as unpredictable. To prepare

us, Schlumberger had built what was essentially a mock drilling rig

on dry land, complete with an enormous separator: a device with a

tank the size of a smallish submarine that is used to vertically

separate (hence the name) sand, water, emulsion, oil, foam, and gas.

It relies on a complex sensor system that dangles down inside the

tank. When everything is working smoothly, it lets you selectively

pour oil from one spout, water from another. However, I can assure

you, everything that can go wrong in a separator does indeed go

wrong.

In our intensive training schedule, we’d spend a long day

learning how some complex, computerized system worked, and then

be released for a few hours into the black January night to blow off

some steam pressure in the legendary pubs of Edinburgh. We’d

come home, pile into our bunks, and try to sleep it off when an

alarm would sound, the lights would come on, and our equivalent of

a drill sergeant would march in to inform us that the separator was

broken and we needed to fix it pronto—no time for pleasantries, no

time for toiletries, now, now, now!

This sort of thing turned out to be typical. Almost daily, some

system or other would get “broken”—actually sabotaged—which

sometimes meshed nicely with what we’d been learning that day,

and sometimes functioned as a refresher for something we’d

learned weeks ago. Sometimes the “malfunction” would happen

when the sun was up, but there must have been something about

the wee hours, because more often than not, that was when

wrenches appeared in the works. How suspicious!

Somewhere along the line, things began to click. Concepts that

I’d vainly struggled to internalize at university began to simply

make sense. A major part of this shift was due to seeing those

concepts taken out of the world of textbook diagrams and put to

work in the conduits, pipes, and valves before me, whose purposes I

now understood. (I’ll return to the importance of context for

learning in the chapters ahead.)

But just as important was the matter of timing. Before, when I’d

crammed for my exams, it wasn’t because I was stupid or lazy. I did

it because it worked—at least in the short term. Indeed, in most

psychological studies of the spacing effect, cramming the night

before an assessment is just as effective as spacing, and sometimes

it can be even more effective on test day. But take that same test

again after a week or a month, and the spaced-out strategy wins out

virtually every time.

I’d understood that, in a general sense, at university. But I’d had

limited time and attention, and once a final exam was over, there

was never an immediate need to revisit the material. So I didn’t.

And in the long term, my retention suffered.

Only later would I begin to consider how curious it was that such

unavoidable educational fixtures as final exams seemed almost

custom-built to promote harmful study strategies. This discrepancy

was, in fact, evidence of a collision point between two distinct

functions of school: the promotion of learning and the

standardization of education. My university’s reliance on

infrequent, high-stakes exams—as opposed to more frequent,

cognitively friendly, lower-stakes assignments and quizzes—

represented a victory of school’s standardizing, winnowing function

over the demands of students’ learning brains. In fact, the entire

overarching, regularized structure of university education,

organized into semester-long courses full of information that, upon

completion, students often never encounter again, runs contrary to

the learning brain’s need for spaced repetition. And while E. L.

Thorndike can’t claim personal responsibility for every standardized

feature of contemporary education—the university term or

semester, for instance, predates his influence—the biological

importance of spaced repetition nevertheless adds an ironic twist to

his legacy. School programs ostensibly set up to identify those

students best able to form useful memory associations, per

Thorndike’s model of the mind, appear to step on the very cellular

mechanisms that undergird associative memory.

My training in Edinburgh, by contrast, was like nothing I’d ever

done, in that its unadulterated purpose was not winnowing, but

rather the promotion of deep, contextualized learning. Knowledge

that, in years past, I would have forgotten soon after I’d committed

it to memory now stuck around as I re-accessed it. (Sometimes, like

when I was roused from bed, I re-accessed it in a heightened

emotional state, which—flashbulb effect!—only helped with

retention.) Soon, I perceived the most wonderful thing happening.

Have you ever noticed how, when you learn a new word, you begin

to hear it everywhere you turn? This was happening to me, but with

engineering principles. Before, I’d been building up stand-alone

memory assemblies and letting their connections fade, sometimes

over and over again. Now, I was building them up, reinforcing them,

and involving them in new associations that, in turn, only added to

the amount of regular exercise my assemblies received.

This was all taking place in early 1990. And so, unbeknownst to

me, much of the research was still unfolding—often in the mind and

laboratory of Eric Kandel—that would help explain why re-accessing

and elaborating on memories strengthens them at a fundamental

level, like how bones grow in the human body.

Today, we know that LTP induction (as observed in neuroscience

labs) and memories preserved via spaced repetition practice (as

observed in psych labs and research classrooms) are aligned, albeit

imperfectly. For instance, both last longer the more spacing is used

during training sessions, but only up to a point; there appears to be

such a thing as too much space. In fact, there are still enormous

holes to be filled in our understanding of the timing question. It’s

not known, for instance, how much spacing, and when, is ideal for

LTP promotion in different types of neurons. Even psych research

into the spacing effect has its limits. We know that if you want to

remember something for a day, you should space your study

sessions a day or less apart; if you need to know something for a

month or more, you should space your studying out by a few weeks,

maybe a month; and if you want to remember something for the

truly long haul, you should revisit it on the order of months, maybe

longer. But no psychologist can give you instructions more finely

tuned than that.

That said, here’s one good rule of thumb for spaced practice: If

you’re going over a topic and so little time has passed that it

requires no mental effort to revisit it, then that doesn’t count as

spacing—that’s closer to massed practice. Once you’ve done a little

forgetting, however, and it takes some effort to relearn the nuances

of a topic, that’s a strong indication that you’re on the right track. If

you want to initiate the hardcore, anatomical changes of late-phase

LTP, you need to convince your neurons that the information you’ve

learned isn’t something to be dismissed like every other

inconsequential event in your day. One way to do so is by revisiting

it when the memory starts to fade. Eventually, it will stick around

for the long term.

But the need to build some space into one’s study practice is no

reason to stop and rest on your laurels. In fact, interleaving—the

term for spacing out your studies by filling in the temporal gaps

with different subjects you hope to conquer—doesn’t just provide a

time-effective way to space out multiple subjects at once. At the

level of associative memory formation, it also allows you to make

connections, where appropriate, between the different things you’re

learning, which can improve overall understanding and recall. (It

also has other, higher-level benefits, which I’ll explore in chapter 5.)

In one clever 2010 study, for instance, two groups of fourth-graders

practiced various types of geometry problems with the same

amount of spacing in between each type, but in one group, the

researchers interleaved the problems, while in the other, they

delivered them in blocks, with spacing provided by filler activities.

When tested afterward, the interleaved group performed twice as

well.

This interleaved strategy, structured perhaps less formally, was

precisely what Schlumberger subjected me to in Aberdeen. At first, I

didn’t like it. (This feeling is normal. In the study mentioned above,

students in the interleaved group underperformed during their

practice sessions; their advantage only manifested afterward.) Later,

however, when my training was done, I felt extremely sure of

myself. Barring a major disaster, it seemed there was very little that

could go wrong on the oil rig that I wouldn’t be able to suss out and

fix. It wouldn’t be overstating it to say that, when the helicopter

touched down and I ducked out onto the salt-flecked helipad, I felt

ready to kick some serious tail.

After a few extra days of onsite-specific training, I began my

work. To start, I was told to shadow an older technician who would

teach me the ropes. And indeed, there were ropes, or rather cables,

everywhere: high-tension lines, pulleys, and weights, which

sometimes had to be toted about by hand. At the end of my first day,

my boss asked me to go get him a counterweight he needed. “Climb

up that,” he said, pointing to the highest spot on the platform, a

metal structure accessible only via a long, slippery ladder, “and tell

the guy up there that you need a long weight.”

This request wasn’t total nonsense: There were weights of all

shapes and sizes on board, including, presumably, a long one. And

so I did as I was told. I climbed the ladder in the freezing rain,

hooking my harness to the metal framework in stages in case I took

a spill, and then told the man at the top what I needed. “Sure,” he

said. “Stay put.” And then he continued going about his business. I

waited.

And waited.

It took me about twenty minutes to realize I’d actually been sent

up there not for a long weight, but a long wait. I wish I’d had the

good nature to laugh when I figured out the joke; I probably cursed.

But I’d learned something: namely, that I had much more to learn.

It was one lesson, emotion-tinged—and, in its way, spaced out—that

will stick with me for the rest of my life.

THE CUTTING EDGE ADVANCES

In the years that followed, I began to look back on my oil-rig period

with a certain nostalgia—and more than a tinge of disquiet. The

training on offer in the petroleum industry is so effective because it

has to be: The business is technical, competitive, and dangerous,

and so its companies have no choice but to invest in their

employees to a degree rarely matched in other industries. That’s a

nice perk for the individuals involved, but then again, you shouldn’t

have to work in petroleum in order to get top-notch, workplace-

ready technical training. As I gained more perspective (and as the

research on climate change continued to roll in), I found myself

wondering whether the cognitively user-friendly aspects of my

training experience could be freed—jailbroken, even—and made

available to learners contemplating fields well beyond the world’s

fields of oil.

Today, owing in no small part to my North Sea experience,

learning has become something I seek out for its own sake—not just

for the knowledge gained, but also for the act of obtaining it. I find

it’s a decent personal ethos; more importantly, it’s also the driving

impetus behind science’s continuing march into the unknown.

And the stuff of memory still certainly falls into the “unknown”

category. Take, for instance, template matching: the notion that a

given cell assembly will fire only after receiving a specific signal.

The principle works really well in deep-learning computer

algorithms, but we have no idea how, or even whether, it works in

the brain. In fact, the synaptic-strength explanation of memory

itself, though well supported, is still just the frontrunner in an

ongoing race, and its victory is by no means guaranteed. As

judicious observers have pointed out, most of its supporting

evidence, though plentiful, is of the “strong-but-circumstantial”

variety.

Very recently, a group of scientists here at MIT found a way to

dig deeper. The story begins in the lab of Susumu Tonegawa, yet

another Nobel laureate, who helped found MIT’s Picower Institute

for Learning and Memory. By 2012, there had been a long-standing

push under way among the world’s neuroscience labs to identify the

specific neurons involved in a specific memory in a vertebrate brain.

That year, a postdoctoral associate in Tonegawa’s lab named Xu Liu,

teaming up with a graduate student named Steve Ramirez, devised a

way to do exactly that, in the brains of laboratory mice. They took a

gene called c-fos, which becomes activated in neurons that have

recently fired action potentials, and packaged in a few genes right

next to it on its chromosome, so that whenever the cell expressed c-

fos, the new genes would get expressed as well. (Imagine a vending

machine that gave you a bonus pack of chewing gum every time you

punched in the code for a Snickers bar, and you get the idea.) One of

the new genes, borrowed from a bioluminescent jellyfish, coded for

a protein that glows bright green in the dark. When the team

shocked the foot of their genetically enhanced mouse, causing it to

form a fear memory, its recently fired memory neurons began

churning out this green fluorescent protein. Later, laid out on a

microscope slide, the cells lit up like the Emerald City at dusk. It

was the first-ever photograph of a memory.

But that was only half the story. That same year, a young

doctoral student named Dheeraj Roy joined Tonegawa’s lab. To

explain the second half of the study, Roy led the way up to his lab

space: a windowless world on the seventh floor of the Picower

building where everything revolved around mice. The elevator was

kept at a sweltering temperature—“to transport mice,” he explained.

“They get cold.” The lab itself sat behind a security antechamber,

where all comers were required to don a lab coat, nitrile gloves, and

hair net for the sake, again, not of humans but of lab mice, which

are often raised from birth in sterile settings and must be protected

from the world outside.

The lab space, the size of a walk-in closet—real estate at MIT is

often at a premium—was mercifully cooler than the elevator and

equipped with four polycarbonate cages, each with metal grilles for

floors and a pair of fiber-optic cables dangling portentously from

their ceilings. Roy turned off the overhead lights and flipped a

number of switches nearby. Circles of violent blue light appeared

beneath each cable, on the floor of the cages.

The second half of Liu’s study, Roy explained, relied on this blue

light. In addition to green fluorescent protein, Liu and Ramirez had

included a gene for a light-sensitive protein called

channelrhodopsin, borrowed from a species of single-celled algae

that uses it to find the sun. When a neuron, tricked into expressing

this protein, is exposed to the right sort of light—specifically, the

blue light issued from the fiber-optic cables—it goes wild, firing off

action potentials like it’s getting paid by the jolt. Since its invention

in 2004, this technique, known as optogenetics, has brought

unprecedented levels of precision to virtually every thread of

neuroscience research requiring the external activation of neurons.

In the team’s case, it gave them the chance to selectively stimulate

only those neurons involved in a brand-new memory. When the

mouse received its shock and developed a fear memory of the cage

where the shock took place, the neurons involved produced

channelrhodopsin. Then, after putting the mouse in a different cage

where there was nothing for it to fear, the team plugged the optical

cables into a port in the mouse’s skull and flooded its brain with

light. The channelrhodopsin, triggered by the light, caused the fear-

memory cells to fire. And the mouse froze in place, transfixed by the

induced memory of its earlier shock.

Here the story takes a somber turn. Professor Liu tragically

passed away in 2015, not long after accepting a faculty position at

Northwestern University. He was just thirty-seven years old.

Depending where the research leads, Liu’s legacy may

nevertheless turn out to be enormous. In a study published in 2015,

Tonegawa’s team added a wrinkle to Liu and Ramirez’s protocol.

After training their genetically modified mouse to fear electric

shocks, they gave it a drug that wiped out all built-up synaptic

strength in its brain, thereby theoretically eliminating its memories.

Soon enough, the amnesic mouse happily sauntered around the

shock cage where it would normally have hunkered down in fear.

Their plan was merely to use this technique to add to the pile of

evidence supporting the synaptic-strength theory of memory, and so

they expected nothing much to happen when they switched the

brain-lights on. They would stimulate the group of cells that had

once contained the mouse’s fear memory, but which was now, with

its interconnections wiped, essentially just a haphazard smattering

of cells. Even with those cells activated, they expected the mouse’s

happy behavior to continue, unchanged.

Which was why, when they flipped on the blue light and the

mouse froze, so did the researchers. The implications were

groundbreaking and immediately controversial. Memories, the team

argued, must be encoded not only by the strength of synaptic

connections, but also, somehow, by their connectivity pattern.

“The 2015 paper’s conclusion was completely unexpected for

everyone in our lab,” Roy said. The team, now led by Roy, followed

up with a pair of papers in 2016 and 2017 elaborating on their

results, and the team’s explanations began to look more and more

plausible.

Not everyone agreed with them. Wayne Sossin, a neuroscientist

at McGill University, acknowledged that the mouse’s freezing

behavior did indeed mean that a memory was being activated, but

raised questions about the MIT team’s conclusions. Tonegawa

“talks about everything stored in the ‘connectivity,’ ” Sossin said

over the phone. But the difference between synaptic connectivity

and synaptic strength? “To me, the two words are synonymous.”

Perhaps, as Roy and Tonegawa’s team suggested, in the encoding of

memories, new connections are forged between pairs of previously

non-communicative neurons, and this new connection pattern, even

in the absence of bulked-up synapses, holds the key to memory. Or,

perhaps less excitingly, some small boost in synaptic strength was

somehow left intact during the team’s amnesia-inducing procedure,

too weak to affect behavior under normal conditions, but strong

enough to reveal itself under the inexorable exhortations of

optogenetics. “I don’t understand the mechanism that he’s

imagining for connectivity that’s not a change in synaptic strength,”

Sossin said. That said, different mechanisms for memory, he

acknowledged, could theoretically coexist. “It’s not mutually

exclusive. And I think one of the things that I like to emphasize is

that not all synapses are the same. Not all connections use the same

rules.”

Memory at the cellular level continues to present a frontier for

new discovery. But, rising above points of disagreement, one

constant remains strong: the importance of spacing and repetition

for lasting memories. In the Tonegawa team’s new model, spacing

only aids in the maintenance of new synaptic connections and LTP,

both of which still appear to be necessary for natural memory recall.

Sossin, meanwhile, has gone so far as to hypothesize a unified

model of sorts that hinges on spaced repetition, with initial learning

events causing new synapses to develop within memory circuits,

and then spaced learning events stabilizing those synapses and

using them to encode memories for the long term.

For too long, we’ve treated spacing as an educational add-on: an

optional strategy that students can choose to ignore. But the spacing

effect is not auxiliary to learning. Rather, it appears to be

fundamental, present even in the minutest neural connections in

extremely simple animals, inseparable from the stuff of memory

itself. The temporal rhythms of memory are baked in: not just

within our brains, but in our very heritage as learning organisms.

Which makes me wonder: Shouldn’t the way we teach better reflect

this biological reality? There are certainly ways to shoehorn spacing

into the traditional academic calendar as it stands—low-stakes

quizzes that continually call back to earlier material, for instance,

and increasingly cumulative exams—but my experience in

Edinburgh and on the North Sea suggests that brave new

educational structures, less beholden to norms and tradition, could

go significantly further in realizing the benefits of spacing.

And perhaps they might carry other, higher-order benefits as

well. If unnecessary impediments to learning exist at even the

fundamental level of associative memory, what will the higher

levels of cognitive science reveal?

\*1 The principal cell of the brain’s neocortex, first described in detail by Cajal.

\*2 We owe much of our early knowledge of neurons and synapses to animals with simple

nervous systems. Our first insights into action potentials, for instance, came from the giant

axon of the foot-long squid Doryteuthis pealeii. Most squids have a giant axon running

stem to stern, and the one belonging to the human-sized Humboldt squid is especially

magnificent: the length of a tall person’s arm, and, at one millimeter in diameter, a

thousand times thicker than human axons. The longest axon in the animal kingdom is

likely the hypothesized connection between the brain and fluke of the blue whale. For

scale, imagine that axon in the Statue of Liberty, running from her head to her sandaled

foot.

\*3 These concerned a man named Henry Molaison, known to the public only by the initials

“H.M.” until his death in 2008. More on Milner and Molaison in the next chapter.

\*4 Ever notice how you can quickly get used to a smell in a room, to the point where you

can’t even say whether it’s still present? That’s habituation, likely taking place in part at

that first juncture in the olfactory bulb, which means that the synapse connecting the nose

to the brain has become temporarily weak. For certain smells, this can come as a relief!

- III -

LAYER TWO: SYSTEMS WITHIN

SYSTEMS

Enter MIT’s Building 46 from the south, and you’ll walk under a

sign that reads “Picower Institute for Learning and Memory.” But if

you walk around the side of the building and enter from the north,

the sign overhead will read something different: “McGovern

Institute for Brain Research.” How a single building can contain two

separate institutes makes a little more sense when you realize the

structure is, in fact, a bridge. It straddles the Grand Junction

Railroad, an eight-mile stretch of single-track, standard-gauge

railway that serves as the lone, tenuous link between Greater

Boston’s southern and northern commuter rail lines. To provide

necessary clearance for the trains passing beneath, the two sides of

the building meet starting only at floor three: a tiled, echoing plaza,

above which soars an atrium that widens with each level, like an

inverse ziggurat. The expanse admits daylight into all corners,

permits McGovern and Picower scientists to wave at each other, and

also happens to weigh precisely nothing—which is exactly what you

want when you’re building over a void. Staring up at the glass roof,

it’s easy to forget that substantial parts of the atrium’s floor and

walls hang in the air, draped between the Picower and McGovern

towers. Although each institute is capable, quite literally, of

standing alone, when they are connected a monolith emerges,

singular in form and function. Building 46 exists for one purpose

above all others: to close a gap.

Cognitive science is a collection of fields separated by gaps in

scale. The Picower is devoted mainly to neuroscience conducted at a

fine, granular level: in and among the brain’s individual synapses

and cells. To get from there to the scale where most McGovern

scientists operate, you’d have to zoom out. Far out, in fact.

McGovern scientists routinely create digital images of the brain

composed of 3-D pixels, known as voxels. Each individual voxel can

contain as many synapses as a nine-hole golf course contains blades

of grass. Many of the brain’s great mysteries, including unanswered

questions about learning and memory, exist between these levels of

resolution. Thanks to work done at the Picower level, we know, at

least in theory, how synapses can encode and hold on to

information. And thanks to work done by McGovern scientists and

their colleagues operating at what’s known as the “systems level”—

that is, in chunks of brain that would be discernible to the naked eye

—we know of regions involved in the formation and recall of

memories. In rare cases, we even have a sense of where cell

assemblies dedicated to hosting certain types of memories seem to

reside. But everything in between those levels of insight—which

specific cells encode which memories, how those specific cells are

chosen, the dividing line between one memory and another

associated memory—these are the sorts of questions that we don’t

yet have the tools or methods to easily answer.

In fact, all of cognitive science is like this: a vast unknown

punctuated with occasional scientific outposts. To explain, let’s tip

Building 46 over onto its side. Picture Picower falling facedown onto

the street and McGovern rising into the air, trailing dirt and debris

and colonial pottery. Now that we have two levels of a vertical

structure of cognitive science disciplines, let’s add more levels,

above and below. For a basement, beneath the now-ground-floor

Picower, we might add a level devoted to genetics and genomics,

since one’s genome wields considerable influence over neural

development. Genetics tools overlap in some places with the

ground-level work done at the Picower, such as in optogenetic

experiments. But we’re still not even close to bridging the gap

between knowing what a few, or even a great many, genes do in

theory, and how in practice that adds up to even a single living

neuron.

The next platform up, the Picower level, benefits, as we’ve seen,

from the techniques of cellular biology and fundamental

neuroscience. It’s sometimes possible to use these methods to

stretch up and probe the darkness separating Picower and

McGovern—to figure out which specific neurons do what in the

brain—but it’s an extremely painstaking and expensive process.

Take, for instance, the team of neuroscientists who, in 2015,

accomplished something similar to what Eric Kandel achieved in

Aplysia, but in the fruit fly brain, a far more complex system. They

isolated a key synapse that grew measurably stronger during a

specific instance of learning, an amazing discovery. And yet, the

looming goal of characterizing a complete neural circuit that fully

accounts for a fruit fly’s learned behavioral change, from stimulus

to new behavior, is still maddeningly far off—and that’s despite the

fact that the entire network of fruit fly neural connections has been

mapped out. Scientists still have to go through that “wiring

diagram” bit by bit to see which synapse does what.

“I have a hope that we can figure out all the circuits from the

sensory input to the behavior output,” said the study’s lead author,

Toshihide Hige, “while I’m still alive.”

Hige, it’s worth noting, was thirty-seven years old at the time.

Happily, however, scientists are working to close such gaps in

two directions at once, not just stretching upward from the cellular

Picower level, but also downward from McGovern’s systems level.

Arguably, the marquee tool at McGovern is the fMRI scanner: the

same doughnut-shaped, powerfully magnetic diagnostic tool you

might find yourself occupying at the hospital, adapted to detect

brain regions that are flush with oxygen-rich blood, a sign of local

activity. Using this technology, scientists can pinpoint currently-in-

use brain regions down to roughly the cubic millimeter. Cellular

neuroscientists would find such brushstrokes absurdly broad.

Considering that our heads contain more than a million cubic

millimeters of brain tissue, however, for scientists studying the

whole brain or large regions thereof, the relative precision and wide

coverage offered by fMRI scanning can feel nothing short of

miraculous.

The stack of cognitive disciplines continues upward, past

McGovern. Imaging tools give way to a variety of psychological

methods, and then, above that, sociological, anthropological, even

economic inquiry. Knowledge gaps persist between higher levels,

too: Cognitive psychologists, for instance, dig downward, stripping

away confounding variables in order to peer into the workings of

thought, while systems-level brain researchers work upward to try

to see which surface phenomena, visible to psychologists, have deep

roots, attributable to neural anatomy and function. The spacing

effect is especially interesting because of its sheer depth, with roots

plunging through regions visible and dark all the way down to the

sub-synaptic level. Other comparable factors exist, however, and

despite their shallower roots, they remain every bit as capable of

making or breaking your chances of learning something.

Over a hundred years ago, E. L. Thorndike suggested that a

person’s knowledge consists of individual memories associated with

one another in an ever-expanding web. It was almost as though he’d

peered into a crystal ball and foreseen the state of affairs residing

today at the Picower level: cell assemblies consisting of, and

interconnected by, beefed-up or enfeebled synapses. What he

couldn’t anticipate, however, were all the processes originating

above the synaptic level that would prove just as critical to when

and how learning occurs—and, consequently, which students are

found worthy or wanting in the educational winnower.

Today, we know far more about those intermediate levels, the

obstacles to learning that can appear there, and what to do about

them. In my mission to help more people develop a lifelong

relationship with learning—expanding, along the way, our notion of

who is worthy of educational investment—two systems-level

research threads hold particular promise. One has to do with the

physical architecture of memory storage in the brain. The other

concerns how fundamental motivating drives, such as curiosity,

intersect with those stored memories. Both threads loop multiple

times through the McGovern Brain Institute at MIT. Let’s catch

hold of them there and see where they lead.

SWISS ARMY BRAIN

The tale of systems-level neuroscience in the past few decades, and

its import for our understanding of learning, involves thousands of

researchers. I’ll focus on two of them, both at McGovern, who have

elevated the idea of a highly compartmentalized brain—a model that

lends itself well to an inside-out, mechanistic approach to

improving learning.

They also both happen to have interesting heads.

That’s one thing you might notice when talking with John

Gabrieli: the levelness of his gaze. He keeps his head perfectly still,

eyes fixed on yours. Perhaps it’s a habit he picked up in the brain-

scanning stocks of the fMRI machine in McGovern’s basement,

running preliminary trials on himself. It’s as though there were

something carefully organized up there, known only to him, that he

doesn’t want to throw into disarray.

Gabrieli is perhaps best known for his pioneering use of imaging

technologies, which he’s aimed at specific neurological disorders as

well as at more fundamental questions, such as the mechanisms

underlying memory and learning. These latter explorations have

fleshed out our understanding considerably—and complicated

matters commensurately.

There’s more to the associations responsible for memory than I

let on in the prior chapter. Remember that banana odor? In the

interest of simplicity, I gave you the impression that the brain’s

association cortices (the poorly defined regions where

representations of the banana’s smell, appearance, name-as-spoken,

and name-as-written reside) amount to an undifferentiated mass of

synapses where memories can be stored essentially

indiscriminately. Picture a slovenly private detective’s office, littered

with files flung so haphazardly that only their owner knows where

to find them, and you get the idea. That impression isn’t wrong,

exactly, so much as outdated: It was the leading theory of memory

organization in the first half of the twentieth century. Although Karl

Lashley came up with the theory in the 1920s, he nevertheless spent

a good chunk of the 1940s trying to disprove it, systematically

damaging lab animals’ brains in an effort to locate the site of

memory traces. It didn’t work. “I sometimes feel, in reviewing the

evidence of the localization of the memory trace, that…learning is

just not possible,” he wrote in 1950. “Nevertheless, in spite of such

evidence against it, learning sometimes does occur.”

The first real indication that the brain relies on a more

specialized filing system arrived in the person of Henry Molaison,

who was known to the public only by the initials “H.M.” until his

death in 2008. In 1953, in a last-ditch attempt to correct his

debilitating epilepsy, Molaison had matching chunks removed from

either side of the center of his brain, a procedure that claimed most

of his hippocampus and several nearby structures. The cure, which

proved largely successful, came at a terrible price. He awoke into an

eternal present, unable to form new long-term memories, a

condition that persisted for the rest of his long life. This tragic

outcome, instantly familiar to anyone who has seen the film

Memento, transformed the science of memory. Initially, research

spearheaded by McGill’s Brenda Milner focused on Molaison’s

inability to form new long-term memories, which clued in

neuroscientists to the importance of the hippocampus and

surrounding structures for the process of long-term memory

consolidation.\*1 Since Molaison still retained memories from his

youth, the hippocampus couldn’t be the final resting place of long-

term memory. Instead, researchers hypothesized, short-term

memories had to somehow pass through the hippocampus,

undergoing some sort of transformation along the way, before being

filed away for good elsewhere.

By the end of the 1950s, it was becoming clear that there was at

least some division of labor in the brain’s memory systems, but the

degree of systematization remained mysterious. Barring further

evidence, it seemed that the organizational scheme might well turn

out to be as simple as a pair of categories labeled “short term” and

“long term.”

Soon enough, however, those categories began to split and

multiply like cells under a microscope. The focus of research into

Molaison’s brain began to slide from what he could not do to what

he could still do, and it proved to be just as revealing. He was, it

turned out, capable of improving his performance on certain motor

tasks, such as tracing a five-pointed star on paper while granted only

a disorienting, mirror-reversed view of his drawing hand. Although

he could never recall practicing this odd task, his skill grew.

Eventually, during one star-tracing session after much forgotten

practice, Molaison exclaimed, “Huh, this was easier than I thought

it would be.”

The upshot of all this work was that long-term memory, once

unitary, became bipartite. Consciously accessible memories of the

sort Molaison reliably forgot—new facts, new words, new personal

history—now fell within the category of explicit memory. Essentially

everything Molaison still could retain, by contrast, became known

as implicit memory, which came to include classical conditioning of

the sort that Kandel had demonstrated in Aplysia as well as motor

and perceptual skills: riding a bike, playing the piano, reading at full

speed.

The idea of implicit memory wasn’t new, exactly, just newly

explicable. In the 1800s, a number of tales had emerged concerning

memory in the face of amnesia. There was the British woman, for

instance, who damaged her memory when she nearly drowned, and

then learned the trade of dressmaking, despite the fact that every

day on the job felt like her first. And then there was the forty-seven-

year-old woman, amnesic as a result of alcohol abuse, who was

pricked by the pin-wielding Swiss psychologist Édouard Claparède,

subsequently forgot the attack, and nevertheless refused to shake

his hand the next time she saw him.

Now explanations flooded in for these historical anecdotes as

well as more commonplace observations, such as the fact that it’s

much easier to forget, say, the atomic weight of tungsten than it is

to forget how to ride a bicycle. Once it was clear that these sorts of

memories relied on different parts of the brain, their different

degrees of stickiness began to make more sense. One paper from

1994, for instance, revealed that Molaison’s star-tracing ability

remained elevated even after a full year’s break from practice. It was

quite literally just like riding a bicycle.

The lead author of that paper was John Gabrieli. From the mid-

eighties to the mid-nineties, Gabrieli and his doctoral advisor, the

late, renowned MIT professor Suzanne Corkin, had essentially

inhabited Molaison’s implicit memory as they produced a lengthy

list of what his brain could and couldn’t remember. Their efforts

received a welcome boost by a newly discovered form of implicit

memory known as priming, which could be used to plumb

subconscious memory associations.\*2 In a typical priming study,

researchers would measure the degree to which encountering a

given cue—a spoken or written word, or, as the field evolved, other

stimuli—made it easier, minutes or hours later, to come up with

certain answers in response to experimental prompts. For instance,

imagine I asked you to study a long list of terms, including the word

meter, and then later, after you’d presumably forgotten that

particular cue, I asked you to fill in the blanks in: “m e \_ \_ \_” with

your choice of either meter or melon. If you (or a statistically

significant set of people like you) chose meter, that could be

construed as evidence of priming. Somewhere in your mind,

researchers hypothesized, a pathway remained oriented toward

meter, and that lingering bias counted as an example of information

storage in the brain—aka memory.

The biggest downside to these sorts of studies was that in even

the most meticulously designed experiments, researchers could

never really tell which results were due to priming and which were

due merely to half-forgotten snippets of explicit memory. Amnesic

patients like Molaison who had no explicit memory, however, blew

this problem out of the water. When Molaison displayed priming, it

had to be the real deal.

Gabrieli kept pushing and the categories of memory kept

dividing. It turned out that Molaison was capable of feats of priming

that people with different memory deficits couldn’t pull off.

Molaison could be primed to solve ambiguous connect-the-dots

puzzles in a certain way, for instance, which didn’t work in people

with Alzheimer’s disease. Gabrieli took this finding as evidence for

some unknown yet qualitative difference between memories of

words and those of images.

By the end of Gabrieli’s PhD program, however, newer, more

accurate tools were becoming available. In November 1991, a

computer-generated illustration of an unfortunate-looking man’s

bald head graced the cover of the journal Science. He had a clean

slice missing from his upper-rear skull, as though he’d leaned

backward (forgive me) into an airplane propeller. A few regions of

the exposed brain glowed orange. It was one of the first fMRI

images ever taken of brain activity corresponding to human vision,

and it served as the opening shot in a revolution. fMRI’s precursor

technology, positron emission tomography (PET), took what

amounted to minutes-long-exposure photographs of milliseconds-

long neural flickers, which was like trying to photograph a

hummingbird’s beating wings using a Civil War–era camera. An

fMRI “exposure,” by contrast, could be made on the order of a single

second (and as a bonus, unlike PET, it required no injections of

radioactive materials). As the technique’s advantages grew apparent,

brain scientists began clamoring for scan time at their local

hospitals’ fMRI machines.

Like many young brain scientists and neuroscience-oriented

psychologists, Gabrieli, who was hired at Stanford in 1991, resolved

to master this new technology, which promised freedom from the

catch-as-catch-can nature of working with people who happened to

have brain lesions. As fMRI researchers slid their test subjects into

their scanners and fed them different stimuli, a picture of a highly

organized brain began to form that stood in stark contrast to the

cluttered-office model of old. There were perceptual brain regions, it

soon became clear, that responded solely to specific categories of

stimuli. The first, and perhaps most striking, of these was

discovered by Gabrieli’s eventual McGovern colleague Nancy

Kanwisher.

—

In the 1980s, Kanwisher was a member of the same graduate school

class as Gabrieli; today, they’re both professors in that same

department at MIT. And like Gabrieli, she too possesses a noggin

that may interest passing observers, but for different reasons. For

one thing, hidden beneath her hair, her scalp is covered in

imperceptible tattoos.

In the early days of transcranial magnetic stimulation, an

experimental technique that involves stimulating the brain with

magnetic fields, Kanwisher found herself in need of exterior

landmarks for her explorations, and so, pragmatically, she and a

graduate student had dots of different colors, including a couple

visible only under a black light, strategically tattooed. Tattoo parlors

were illegal in Massachusetts at the time, so they had to travel to

Providence, Rhode Island, where a beefy, ink-covered artist did the

precision work. Kanwisher laughs about it now: “That was like

twenty years ago,” she said. “It kind of failed. It didn’t work for shit,

but it was amusing.”

Before that, in the early 1990s, she was one of the hungry young

scientists fighting for scan time in Boston. The pressure was on to

come up with a big result as quickly as possible; she didn’t have a

major research grant, MRI usage was expensive, and a number of

competitors were vying to snatch away her MRI access at

Massachusetts General Hospital. She was searching for regions

devoted to the visual recognition of shapes, but nothing was turning

up in the scanner. To tighten her search, she dug into the literature

concerning a region in the back of the right hemisphere that, when

damaged, caused people to lose the ability to recognize faces.

“I had never worked on face perception because I considered it to

be a special case, less important than the general case of object

perception,” she later recalled. “But I needed to stop messing

around and discover something, so I cultivated an interest.” She

dove in: literally, into the middle of the fMRI machine, where she

painstakingly tested her own brain’s responses to faces and all sorts

of other visual stimuli. A promising, glowing region appeared in the

machine’s mockups of the rear of her right hemisphere, and when it

also showed up in other people’s brains, she permitted herself to get

excited. If the region, dubbed the fusiform face area, really was

integral to the identification of faces, then possibly other, similar

regions existed in the brain’s perceptual systems—maybe even

predominated. “This finding fit the broader idea that the mind is not

a general purpose device,” she later wrote, “but is instead composed

of a set of distinct components, some of them highly specialized for

solving a very specific problem.”

Kanwisher only described the fusiform face area in 1997, long

after fMRI’s potential first became apparent. The reason it took so

long had to do with the differences between individual brains.

People’s bodies vary as much on the inside as they do on the

outside, and the brain is no exception—which is a problem when

you want to locate the same tiny brain regions in different people.

Systems have been created over the years to systematically describe

brain locations, including a coordinate system that works sort of

like latitude and longitude, but due to our natural variation, the

same structure can show up at different coordinates in different

people. What Kanwisher and others figured out (several teams

stumbled onto this technique independently that same year) was

how to locate brain regions functionally. Defined functionally, the

location of, say, Boston wouldn’t be 42.3° N, 71.1° W; it would be

“the place where all the people live near the mouth of the Charles

River.” In the same sense, Kanwisher defined the fusiform face area

not by its neural GPS coordinates but rather as the region in the

fusiform gyrus\*3 that responds significantly more vigorously to

faces than to control stimuli.

Once you have your study subject’s functional region mapped,

then you can ask questions of it, like whether it responds to upside-

down faces, or faces with no eyes. And so, painstakingly, you can

start to home in on the filters that the brain’s perceptual systems

use to make sense of the world. Under this new form of scrutiny,

highly specialized brain regions, once obscured by individual

variation, began to emerge from the haze of imaging data like

gorillas from the mist.

And that brings me to the other thing that’s so noteworthy—and

inspiring—about Kanwisher’s head. In 2015, she was diagnosed with

lymphoma, from which she has since fully recovered, but which

necessitated a chemotherapy treatment that threatened to claim her

hair. She decided to turn the loss into an opportunity to teach a

video lesson on the brain’s new functional anatomy. In a single,

high-stakes take that has since been viewed more than 200,000

times on YouTube, Kanwisher gestures to a 3D model of her brain,

rotating on a screen behind her, which has a number of her own

personal specialized regions highlighted. “Where are each of these

regions inside the head?” she asks the camera. “Well, it’s kind of

hard to tell with all the damn hair in the way.” And with a decidedly

un-Gabrieli-esque flip of the head, she gathers up a lock of hair into

her fist and cuts straight across with scissors. Fast-forward a minute

and she’s seated on a swivel chair, completely bald, with her

graduate student spinning her around, drawing standard anatomical

regions on her scalp in black, and, in red, blue, purple, and green,

Kanwisher’s own specific functional regions—regions only

uncovered in the wake of her description of the fusiform face area.

Today, there appears to exist a whole suite of these perceptual

functional regions, many of which run along the side of the brain:

one for music and another right next door for pitch; another for

bodies; another for places. From an evolutionary perspective, most

of these make intuitive sense: You can imagine how it might be

advantageous to know, without having to think about it, whether a

face belongs to someone you recognize or not, or whether a

brandished object constitutes a threat. Because these sorts of visual

filters would presumably have benefited our evolutionary forebears,

there’s currently a robust debate ongoing about the degree to which,

say, the filters involved in facial recognition are the product of

instinct or experience.

However, there is one functional perceptual region that can’t

possibly be innate, because it responds to stimuli that only came

into existence five thousand years ago. Tucked in snugly next to the

fusiform face area sits a tiny region known as the visual word form

area—or, more colloquially, “the brain’s letterbox.” It is the part of

the brain that scientists believe permits the near-instantaneous

recognition of letters. Not only does such a surprisingly specific

region exist, but it is shockingly invariant: barring serious medical

problems, it’s always found in the same place across individuals,

cultures, languages.

“Why does that land in a systematic location?” wondered

Kanwisher. “To me that doesn’t make sense. Right? Like, given that

there isn’t a prior evolutionary history of people reading, how does

it land always in the same place?”

In a dramatic departure from the messy-office model of

information storage, a highly specific category of memory—the

shapes of letters, and the identities of small groups of letters that

signal the sound and meaning of written words—needs to be filed

away in a very specific location. And if that doesn’t happen properly,

or if the connections servicing the letterbox and other crucial

language-processing regions develop atypically, the ramifications

can be significant.

The most common example of this is dyslexia: reading

impairment at the level of individual words. As the 1990s wore on

and the receipts continued to come in regarding the role of the

letterbox and other regions involved in reading, the attention of

systems-level researchers began to swivel in interest. Even the level

head of John Gabrieli began to turn.

THE DYSLEXIC BRAIN

Gabrieli had spent the bulk of the 1990s running all things imaging-

related at Stanford, where he focused on memory—especially areas

where memory intersected with medical issues: Alzheimer’s,

amnesia, schizophrenia, Parkinson’s, Huntington’s. All the while,

one non-medical area continued to hold his interest: reading, a

holdover from his Molaison research. By the late 1990s and early

2000s, a number of baseline rules concerning the functional

anatomy involved in reading had become clear.

Research in patients with brain damage, and in patients whose

brains had been electrically stimulated during surgery, had long

hinted at the existence of general provinces involved in the

production of speech, the auditory recognition of speech, and visual

word recognition. What these early findings—going all the way back

to 1861 in one case—couldn’t tell us, however, was how these parts

worked together. By the 1980s and 1990s, brain imaging was

changing the game, making it possible to visually trace some of the

sorts of connections that Gabrieli had been exploring via priming.

Sounding out the linkages in the auditory processing of words, for

instance, might once have necessitated the tactic of asking amnesic

patients to choose between homophones (primed with “taxi,” would

they later write “fare” or “fair”?). Now, however, an fMRI researcher

could present study participants with either a written or a spoken

noun, and then scan their brains for regions that became active

when they read it silently or out loud, or responded to it with a

related verb. Taken together, this sort of work suggested the

beginnings of a complex flowchart for how written and spoken

information shape-shifts around the brain.

The most important thing to know about this flowchart is that

there are parallel routes involved. Let’s try it out with a simple

written word, like peanut. Presumably, when you read that word, a

number of associations come to mind: the appearance and taste of

the legume, baseball, Mr. Peanut, and so on.

How does your mind jump from the word on the page to the idea

of a peanut? To start, the image of the written word enters your

brain via your retinas, where it undergoes a series of basic visual

processing steps. The recognition of the sorts of shapes used in

written language selectively activates a pathway leading to the

brain’s letterbox region, which serves as a filter for incoming letters,

identifying which are present and in which order. It efficiently

differentiates among similar-looking-but-different letters (C and G;

i and j) while bundling different-looking-but-the-same letters (g and

G; a and A). The letterbox also doesn’t discriminate between

handwriting and print, or size of type. All told, the letterbox imports

letter-shaped lines and turns them into letters-in-the-abstract.

These are then organized into small groups, including graphemes,

which correspond to the letters’ sound-as-spoken (in “peanut” there

are five graphemes: p-ea-n-u-t), as well as morphemes: the smallest

unit of written language that carries meaning (in our case, “pea” and

“nut”). These sorts of processing steps then inform further brain

activity, which proceeds along two general routes. Both operate

simultaneously, but one or the other picks up the bulk of the work,

depending on what kind of word you’re reading. If it’s a familiar

word like peanut, most of the action follows what’s known as the

“deep” reading route: where the letters on the page communicate

more or less straightforwardly with the cell assemblies that

correspond to the “meaning” of the word, which are believed to live

in a distributed network known as the semantic lexicon.

The other, “surface” route, as opposed to the deep route, takes a

less direct path to the semantic lexicon—but more on that in a

minute. First, it’s worth mentioning what we don’t know about the

role of memory in reading. For one thing, we don’t know where any

given entry in the semantic lexicon lives. The same is true for facial

recognition: we don’t know where our actual face representations

reside. “I can close my eyes right now and imagine my mother’s

face. Boom, there it is,” said Kanwisher. But “where is that memory

stored? We have no freaking idea—and I find that scandalous! I

mean, it is so embarrassing and scandalous to me that after 20 years

of working on this, I have no idea. But I don’t, and I think the field

doesn’t.”

We do know, however, that each functional region lights up

selectively for its preferred stimulus, and moreover, damage to such

areas tends to result in specific forms of “blindness.” A lesion in the

fusiform face area can cause prosopagnosia, aka “face blindness,” or

the inability to recognize and differentiate between faces. And

damage to the letterbox can cause alexia, aka “word blindness”: the

acquired inability to read. Even if the representations of faces and

word meanings live somewhere unknown in the brain, the

perceptual filters needed to process incoming facial and written

information likely exist within the fuzzy borders of their respective

functional regions. And since the filters for written language are

certainly learned, not innate, it’s likely that, in the brain’s letterbox,

we have the resting place of a very specific type of memory. The

messy-office model of memory organization, then, falls away in

favor of something closer to what Kanwisher calls a “Swiss Army

knife” model: a brain filled with specific tools that perform specific

functions. In the brain’s letterbox, memory itself becomes a tool. Its

nebulous, bushy associations become hammered flat, honed into a

surgical blade that, no matter your native language, is always found

in the same spot, and always serves the purpose of cleaving abstract

information from shapes. In a very real sense, then, everything

you’ve ever read and subsequently remembered was built using

tools constructed from prior memories. When you stop to think

about it, the whole memories-upon-memories structure can start to

seem so precarious, so improbable, that you, too, might want to

think twice before making undue head movements.

And indeed, your instinct wouldn’t be wholly wrong, because as

in any complex system, problems do crop up. The 5 to 12 percent of

children who experience reading difficulty due to dyslexia can

quickly find themselves with relatively sparse semantic lexicons

relative to their age cohort, which makes it harder to read later in

childhood, which in turn makes it harder to learn other things via

reading. There are multiple causes of dyslexia (multiple dyslexias,

really), but many cases appear to involve the atypical development

of long, physical pathways in the brain: information superhighways

connecting distant language-processing centers. Surprisingly

enough, the reading route most affected in dyslexia doesn’t appear

to be the deep route running from the letterbox to the semantic

lexicon, but rather the more circuitous surface route I mentioned

earlier, which first leads to representations of the sounds of

syllables and words, and only then proceeds to their meanings.

Assuming you don’t have dyslexia, this pathway leaps into action

when you encounter a new word for the first time and sound it out

—which, when you’re first learning to read, happens frequently.

Later, the auditory middleman can be cut, and reading can proceed

more automatically.

In developmental dyslexia, however, things happen differently.

There are a few hints as to why, visible way up at the psychological

surface levels of cognitive science. Someone with dyslexia might, for

instance, have trouble saying what the word game would sound like

without the g, or struggle to sound out made-up words. With the

tools available at the systems level of neuroscience, it becomes

possible to see where, anatomically, these effects might arise.

In 2000, Gabrieli, as part of a team led by the Swedish cognitive

neuroscientist Torkel Klingberg, aimed a new technique at this

question. Diffusion tensor imaging, a cousin of fMRI, analyzes the

predictably random movement of water molecules for non-random

trends—such as those that occur when water molecules are confined

to the tiny tubes that are neuronal axons. The technology’s

introduction in 1994 led to a series of breakthroughs in our

understanding of how different sections of the cerebral cortex

connect to each other. The cerebral cortex, which is the site of just

about everything brain-related I’ve discussed in this chapter,

consists mainly of a thin layer of neuronal cell bodies, known as

gray matter, that blankets the whole surface of the brain. As

Kanwisher puts it in her head-shaving video, the cortex is about the

size and thickness of a large pizza, and the folds of the surface of the

brain help the entire pizza fit inside the confines of your brainpan.

Just beneath the cortical surface is a different tissue, known as

white matter, which consists less of neural cell bodies and more of

their long, tubular axons, which act like a sort of switchboard

connecting different chunks of gray matter in all different

directions. With diffusion tensor imaging, it became possible to map

out bundles of white-matter axons, which, sure enough, turned out

to connect brain regions that seemed to correspond to different

reading-related tasks. In their 2000 paper, Gabrieli’s team revealed

something strange: A super-long-distance white-matter pathway,

apparently involved in reading, appeared to be directionally

disorganized—woolier, bushier than you’d expect—in dyslexic

brains. A series of follow-up studies undertaken by Gabrieli and

others ensued, and continued after Gabrieli joined MIT’s McGovern

Institute for Brain Research in 2005. As it currently stands, there

are four major suspect white-matter pathways, two of which run

essentially the full length of the brain, that appear to be less

organized in dyslexia. One of these, known as the left arcuate

fasciculus, is deeply involved in phonological awareness, or the

ability to mentally manipulate the sounds of spoken language, a

crucial part of the surface route in reading.

“It actually connects the posterior—the back part—of the reading

network with the front, and that’s quite interesting,” explained

Nadine Gaab, Gabrieli’s former postdoctoral student and current

frequent collaborator, a professor at Harvard Medical School and

Boston Children’s Hospital. Information flow between those areas

is necessary for achieving reading fluency and reading

comprehension, she said, and abnormalities in that flow could

potentially account for many of dyslexia’s manifestations.

PULLING UP THE ROOTS

In addition to disorganization in the brain’s sinews, Gabrieli and his

collaborators have raised another possible explanation for dyslexia.

Both the symptoms and associated imaging results may be related

to an underlying problem with synaptic plasticity: the ability,

discussed in the previous chapter, of synapses to selectively

strengthen and weaken. In this hypothesis, this seemingly general,

systemic problem only affects reading because of all the things we

do, reading is spectacularly, perhaps uniquely, demanding. “There is

no other human behavior that approaches reading’s demands for

coordinating multimodal perceptual representations and cognitive

processes,” write Gabrieli and his coauthors. “In this way, a general

neural dysfunction that is subtly detrimental to other behaviors

may be substantially detrimental for learning to read.”

Stepping back, it may seem strange that there are multiple

conceivable points of failure affecting reading, and reading only.

After all, it’s not something we evolved to do. Most other things

we’ve started doing recently in our species’ history—cricket, video

games, needlepoint—don’t each have their own specific learning

disorder, do they?

In the case of reading, there is so much that can conceivably go

wrong because it’s not a new application of classic tricks (swinging a

cricket bat is not so different from swinging a wooden club), but

rather a hack of our preexisting neural equipment. It goes so far

beyond the design specifications of our brain’s architecture that, if

our heads came with a warranty, reading would probably render it

void. We’re already pushing the envelope of brain function so

aggressively, it seems, that the loss or compromise of any of the

biological machinery involved can easily imperil the whole

enterprise.

To return to the brain’s letterbox, a growing contingent of

researchers has begun to suggest that its location is so consistent

precisely because it couldn’t possibly exist anywhere else: those

letter-detecting perceptual filters must be situated where fibers

carrying shape-related information from the eyes converge on

connections leading to both the shallow and deep reading routes. In

2016, a mammoth team-up of scientists—featuring Gabrieli, Gaab,

and Kanwisher—produced something close to a definitive

explanation for the letterbox’s mysteriously consistent location. By

comparing connectivity patterns in the brains of pre- and post-

literate children, only the latter of which contain a letterbox region

(remember, the letterbox, like the fusiform face area, is defined

functionally, so it only appears after you learn to read), the team

was able to demonstrate that the presence of connections in the

younger children presaged where the letterbox showed up a few

years later. As they wrote in the paper, “the functional fate of a

given cortical region” may be preordained by “its connectivity

fingerprint.”

Put another way, the hunk of long-ago-evolved, shape-

recognizing cortex in which the brain’s letterbox selectively squats

is a highly specialized piece of neural machinery, built to translate

visual shape information for the use of other regions near and far.

So particular is this setup, in fact, that one school of thought even

suggests that, far from our brains adapting to process written

language, perhaps history has selected for the survival of written

languages that meet the strict requirements of our brains. In this

theory, the surprisingly short list of line shapes that form the

backbone of virtually every written language—including those with

characters—exists for the simple reason that those are the sorts of

shapes that our visual processing system can parse quickly and

automatically. “Reading itself,” writes the French cognitive

neuroscientist Stanislas Dehaene, “progressively evolved toward a

form adapted to our brain circuits.”

But don’t mistake those circuits’ specificity for total inflexibility.

In the case of dyslexia, it is possible to mitigate its effects, especially

if you catch it early enough. The trick, once a catch-22 but no longer,

is to identify children at high risk of developing dyslexia—before

they learn to read. Thanks to our growing understanding of the role

played by speech and auditory processing in dyslexia, it’s become

possible to identify pre-literate children who might benefit from

specialized interventions through such tests as asking whether two

words rhyme, or by asking them to name a series of images in rapid

succession. And now, in an effort to catch dyslexia at an even earlier

age, Gaab has developed a computer app that turns such tests into

games involving zoo animals. The app’s main screen, a forest path,

looks just like the parkside view outside her window at Boston

Children’s Hospital.

There is no doubt that the brain, especially the young brain, can

be helped to overcome challenges posed by dyslexia. The

mechanism for how these tactics work, however, remains

mysterious. In the most straightforward explanation, practice

simply strengthens the synapses of anatomical structures that

would otherwise display reduced activation. “But just as often,” said

Gabrieli, people with dyslexia “also see the apparent growth of

pathways, let’s say, in the right hemisphere, not their typical reading

hemisphere.” This sort of development is evidence of a rerouting of

information. “The thought is maybe you’re not so much regularizing

the left hemisphere reading pathway as you are promoting the

development of an alternative pathway,” he said. There are “some

hints that some of the best outcomes in dyslexia are those who

develop an alternative pathway, as opposed to modulating the

typical pathway.”

The recruitment of alternate pathways also occurs in dyslexic

learners struggling to read on their own, but, in the absence of

expert help, this unaided process is usually frustrating. A region in

the left inferior frontal cortex associated with syntax and speech

often goes into overdrive, which doesn’t help—it is, as Dehaene

writes, “a brave but often fruitless endeavor”—but it does testify to

the effort exerted by many learners with dyslexia. The disorder,

striking at the systems level of neuroscience, hinders even the most

motivated learners, and it’s been shown time and again to have

nothing to do with general intelligence or aptitude for learning.

It is not alone, either. In fact, reading is not the only highly

demanding learning task that requires the precise interplay of

memory and perception. The same can be said for at least one other

human endeavor: mathematics. Indeed, a consensus is coalescing

around the existence of a sibling learning disorder of dyslexia,

known as dyscalculia.

“It’s a smaller area, a more recent area. In many ways, it’s kind

of like a fifteen-years-later version of dyslexia,” said Gabrieli.

“Up to forty percent of kids with dyslexia also develop

dyscalculia,” said Gaab, “so there must be some overlapping early

mechanisms. But we don’t know anything about it.”

How did dyscalculia remain hidden for so long? The answer may

be as simple as the fact that you can get away with being “bad at

math” in a way that is not true of reading. “If you can’t do math, you

pretty much can be very successful,” Gaab said. “You can be a

professor of English at Harvard, right, without doing any math. But

if you can’t read, you will have a really hard time.”

As both dyslexia and dyscalculia become more comprehensible

to neuroscientists, their existence raises important questions about

whom our standardized education systems have historically

permitted to advance, and whom they have winnowed. Turn-of-the-

century ideas about intelligence and aptitude, simply put, were not

built to deal with something like dyslexia, which becomes explicable

only when you move up a level on our cognitive high-rise: when you

stop worrying about how memory associations form and start

grappling with where they form. As a result, dyslexia has interfered

with individuals’ educational trajectories ever since the modern

rules of school were built on E. L. Thorndike’s template. Only

recently have we begun modifying these rules to be more forgiving,

such as by granting students extra time on exams. For all we know,

dyscalculia could be having a similar effect, undiagnosed and

unacknowledged.

What else, lurking out there in the darkness surrounding

systems-level neuroscience, might be concealing human learning

potential from the systems that are supposed to detect it? What

leviathans swim past the windows of McGovern at night, felt but

never seen? Or, considering the situation more optimistically, what

bounties exist out there, waiting to be reeled in, that can make

learning more user-friendly, more effective, more inclusive?

READINESS TO LEARN

The outline of one of these figures flitted past Gabrieli’s lab in 2011.

That year, Julie Yoo, a postdoctoral associate, spearheaded an

investigation of the parahippocampal place area, a functional region

first identified by Kanwisher and the University of Pennsylvania

neuropsychologist Russell Epstein that appears to do for places and

scenery what the fusiform face area does for faces. Yoo and the rest

of Gabrieli’s team (including Gabrieli’s spouse and frequent

collaborator, the neuroscientist Susan Whitfield-Gabrieli) were

hoping to find out whether activity patterns in the brain could be

used to predict a state of “preparedness to learn.” The open question

had puzzled scientists going as far back as Thorndike, who, in his

canonical “Law of Readiness,” had observed that there were

moments when an inexplicable switch seemed to flip in the brains

of his test animals, and learning, normally “satisfying,” became

“annoying.”

Identifying a ready-to-learn state by direct fMRI observation of

the full brain was impossible—there was too much brain to watch,

and the relevant patterns might well be tiny—but the small size and

high specificity of functional areas presented a unique opportunity.

The team narrowed their gaze to just the parahippocampal place

area and monitored it for activity patterns, while their MRI-bound

research participants attempted to memorize and recall pictures of

scenery. The approach paid off: The team identified an activity

signature that predicted how well study subjects would remember a

given scene.

The study was simultaneously groundbreaking and of little

practical use. You could theoretically find a readiness state in the

brain, but you’d have to be teaching students lying inside an MRI

machine to take advantage of it. And anyway, the study’s findings

only applied to memory for places, not facts. More than anything, it

was a proof of concept. “Can you measure, in the brain, states of

brain function that are conducive for a specific kind of learning?”

Gabrieli asked. “As modest as that goal sounds, that hadn’t been

done before.”

Mission accomplished, Yoo moved on to another job, and

Gabrieli swung his sights back to dyslexia and other disorders.

When I became aware of the study, however, it stuck with me—not

so much due to the idea of a brain state conducive to learning, but

because its existence suggested the opposite must exist as well: a

state of unreadiness. Although it was not, strictly speaking, a

disorder, since it likely affected everyone, “unreadiness to learn”

was still a threat. Like dyslexia, it could potentially throw education

off track. It, too, seemed to have roots extending down to the

systems level of cognitive science. And as with dyslexia, we didn’t

have to accept its effects.

—

As I’ve already discussed, my academic performance suffered in my

final years at university, in part because of the timing of how the

material was taught. There was more to it than that, however, which

I now believe had to do with a particularly stubborn form of

unreadiness to learn. My difficulties came to a head at one specific

point in the semester. My professor—a leading light in his field; it

wasn’t like my university was skimping on instruction—was

teaching my classmates and me about the relationship between

fluid dynamics and the speed of sound.

At a surface level, supersonic flow isn’t really that complicated.

Basically, when you have a fluid moving through a tube and a partial

blockage occurs—a pinch in a garden hose, a control valve in a pipe

—it creates a choke point, through which the fluid can shoot at

extremely high speeds. The lecture wandered off into the subject of

shockwaves, which I got, but couldn’t figure out why they would

matter for any sort of engineering that didn’t have to do with

supersonic aircraft. My professor also made a vague reference to the

“back-propagation of information,” but I didn’t understand how it fit

in.

Between that lecture and the subsequent exam, every time I

cracked open the relevant section of my textbook, my eyes rolled

into the back of my head. I knew I should want to figure it out, but

it just…wouldn’t quite fit. The experience, I decided, was like tissue

rejection. It was as though my mind couldn’t find a way to make

this new information matter in a useful way, and so classified it as a

foreign object.

Fast-forward a year to my job on the North Sea. The rig I was

working on wasn’t the permanent kind, built into the seafloor, but

rather a floating platform designed for exploration, typically by

plunging a pipe into the seabed and measuring what comes up.

Geologists can divine a lot about what’s underground by the

pressure of the initial stream of oil produced and how quickly it

tapers off. The steadier the pressure, the more oil is likely down

there, but measuring this value can be an uncertain business, since

the changes you’re looking for can be minuscule, and in the

meantime you’re standing on a sloshing watercraft filled with

exceedingly complex equipment maintained by, in my case,

profoundly inexperienced deckhands.

I was working on this system when I had an epiphany so great I

nearly fell into the sea. When the oil flows to the platform, it passes

through a closeable choke valve. The platform’s geologists

monitored the pressure of our exploratory well at a point upstream

of this valve, but pressure fluctuations emanating from downstream

of the valve had the potential to throw off their readings. To avoid

this, my colleagues and I were told to “choke the flow,” which would

cause the flow to move faster than the speed at which sound travels

in oil. That was when I finally got it. “Sound” is actually made out of

pressure waves: when you speak, you’re sending a signal of high-

and low-pressure pulses through the air. A sound wave (or pressure

wave—same thing) that moved upstream through the column of oil

and reached the geologists’ instruments could easily throw off their

highly sensitive readings. If we kept the flow choked, however, and

the outflow fast enough, a pressure wave could never advance past

the choke point; it would be as futile as shouting a message at a

retreating Concorde jet. Moving fluids do indeed carry information,

I realized, assuming you’re the sort of person who cares about

pressure readings. And, just like my professor had said, that

information can’t back-propagate when a choke is tight enough.

Suddenly, I was eager to retrace my steps and figure out all the

other details on the subject that I’d tuned out at university. Because

these events predated the World Wide Web, however, I had to

content myself with badgering my more senior colleagues about it,

which, to their credit, they put up with for far longer than strictly

necessary.

Later on, when I’d calmed down, I wondered why I hadn’t been

able to understand what my professor was telling me the first time

around. What had been the blockage? Had there been, dare I say, a

choke point of sorts in my brain? And if so, what had opened the

valve?

THE CURIOUS BRAIN

In 1994, the Carnegie Mellon psychologist George Loewenstein

articulated a theory that hinted at an answer to questions like mine.

When a brain detects a gap between the knowledge it contains and

the knowledge it might obtain, he suggested, the not-altogether-

unpleasant sensation known as curiosity can result.

One sort of curiosity manifests as long-term fascination with a

given topic: Asterix comics, podcasts about grisly murders, sports

news, that sort of thing. Loewenstein and the brain scientists who

followed him wanted to know more about a different sort: a kind of

fast-twitch curiosity. Let’s say you just found out—oh, to pick an

example at random—that there is a single known species of moth

that would happily bite through your skin and drink your blood,\*4

and its range is spreading. The impulse that is possibly sending you

hurtling toward Google at this very moment is, in these scientists’

reading, a drive state just like hunger, thirst, and the sex drive, as

well as pathological states such as drug addiction. Entire subfields

of psychology and neuroscience have developed around each of

these drives, digging into what triggers them, when, and in whom;

and how they momentarily outweigh other desires. In the case of

curiosity, where the substance desired is information, the vagaries

multiply. What makes a given chunk of information feel highly

desirable, and what renders others effectively inert—as useless to

the curious mind as a handful of gravel to a hungry stomach?

By the mid-aughts, fMRI researchers were digging into the

curiosity question and turning up clues. A small monetary reward

for learning, a team including Gabrieli and Whitfield-Gabrieli

determined, could spur activity in the hippocampus (the home of

long-term memory consolidation) and cause information to linger

for the long haul. They wondered if a similar, intrinsic anticipation

of reward, such as that created by a state of curiosity, might have

the same effect on memory storage. But the more they uncovered,

the more challenges seemed to crop up. “Certainly, curiosity would

be a form of readiness-to-learn,” Gabrieli explained, but

unfortunately, “the brain turns on in fifty different ways” upon

encountering something it finds interesting, which makes it difficult

to pinpoint what’s happening mechanistically. Ultimately,

curiosity’s activity patterns proved so overwhelming that his group

found itself looking for ways to exclude curiosity in their search for

a single, stand-alone, readiness-to-learn brain signature.

Conveniently, their study of remembered scenery made for “very

bland materials,” he said, which allowed them to identify a type of

readiness to learn that appeared to stand independent of curiosity.

Other groups, meanwhile, took the opposite approach, attacking

curiosity directly. A few years later, in 2014, a team out of the

University of California, Davis, provided a tantalizing glimpse into

what, precisely, curiosity does in the brain. While feeding trivia

questions to their study participants, the researchers also showed

them a constantly changing feed of photos of human faces.

Afterward, the participants were more likely to remember a face if it

had appeared during a moment of curiosity—curiosity, that is, for

trivia information that had nothing to do with faces. When you’re in

a state of curiosity, it seems, the potential for long-term memory

formation gets boosted universally, for all sorts of memories—a

process that unfolds, in the words of the authors, “via dopaminergic

facilitation of hippocampal LTP.”

You read that right: LTP, or long-term potentiation, the synaptic

star of sticky memory. As near as systems-level neuroscientists can

figure, curiosity is like rocket fuel for LTP formation in the parts of

the brain critical to long-term memory storage.

And thus, however tenuous the connection, research at the first

two levels of our cognitive high-rise—cellular and systems—meet.

The fact that curiosity is what brings them together is fitting. The

difference between curiosity on an individual level and the

collective, curiosity-fueled effort that is science, after all, is one of

degree, not kind. It’s all about closing information gaps.

The how behind the why of all this hinges on something I

alluded to in the previous chapter: additional circuits of neurons

that ride herd on those responsible for the grunt work of memory.

Memory neurons communicate mainly through glutamate, which is

by far the most common neurotransmitter in the nervous system.

Higher, managerial circuits, meanwhile, wield other

neurotransmitters that can have a variety of effects, as in the

flashbulb-like memory storage Eric Kandel observed in Aplysia. In

the case of human curiosity, it appears that a managerial group of

neurons delivers the neurotransmitter dopamine to the

hippocampus, causing memories there to become stickier.

What’s so fascinating about these signals in the case of curiosity

in particular, as opposed to hunger or thirst, is their point of origin.

The hippocampus itself appears to determine whether incoming

information is worthy of curiosity. Upon finding in the positive, it

sends out excitatory signals to brain regions associated with the

anticipation of reward; these regions then return the favor by

sending dopamine signals to the hippocampus, telling it to turn

new, incoming information into long-lasting memories. The

hippocampus, in short, tells itself when to double down on

information storage. The question of what triggers curiosity, then,

may very well boil down to this: What sort of information, when

acquired, causes the brain to hunger for more?

—

When I could simply not make myself feel curious about chokes in

fluid dynamics, I was attempting to overrule some fairly

fundamental drives in my brain. Both metaphorically and

neurologically (given that curiosity resembles hunger), it was like

entering a hot-dog-eating contest on a full stomach. I wasn’t hungry

for this knowledge, and I couldn’t convince my brain to reward me

for taking it in.

But on the oil platform, something shifted. With a bit of context,

it seemed that I had crossed into a sort of Goldilocks zone, where I

knew just enough to be able to file away more information—a state

similar to what the influential Soviet psychologist Lev Vygotsky

called the zone of proximal development. How, though, could one

little injection of knowledge trigger a drive state in my brain?

The work of Jacqueline Gottlieb, a neuroscientist at Columbia

University who specializes in curiosity, may contain an answer. In

decades prior, she explained, the rules of thumb scientists believed

to animate curiosity boiled down to either neophilia—the desire to

explore anything new in your environment—or the so-called

information gap hypothesis, which holds that curiosity ensues

whenever the available information in your environment appears to

be greater than what you already know. Both theories have

drawbacks, however. The neophilia explanation ends where the

dark, scary basements of the world begin; sometimes we’re content

to let the unknown remain unknown. The problem with the

information-gap hypothesis, meanwhile, is that true information

gaps are rare in the wild; more often, you don’t know what you don’t

know. In a trivia contest, the missing chunk of information is clear:

it’s the answer to the question. There are certain similar situations

with known unknowns, “like when you read a mystery novel, or

when you watch a movie,” Gottlieb said. “It’s undeniable that you’re

riveted and you expect a certain informational flow.” But far more

often, whether you’re a human in a classroom deciding what to do

with your life or one of our primate relatives exploring a new

environment, there are no such guarantees. “Curiosity is about

learning, and it’s about learning when you don’t have a lot of

constraints in the big wide world,” Gottlieb said. In most situations,

you’re surrounded by far more data than you’d ever want to process,

let alone remember, and so your brain must invoke curiosity only

sparingly.

As a result, Gottlieb has suggested, a meta-strategy takes over—

inclusive of, but not limited to, information gaps and neophilia. In

what she calls the learning-progress theory, whenever you

encounter a chunk of information that forces you to change or

reframe your prior body of knowledge, curiosity is likely to follow.

In the case of an information gap established by a trivia question,

the information contained in the question suggests enough to draw

you into a quest for more. And in the case of a more open system—

the “big, wide world” Gottlieb alludes to—your curiosity flows only

to the subset of available sensory information that augments or

challenges what you already know.

A classroom, crucially, is an example of a big, wide world. A

lecturer like me might think that he’s the only source of

information in the room, but even in the days before smartphones

and laptops, that was never true. Other students, a bird outside the

window, a fly in the light fixture—these things have always

competed for students’ attention. Even if a teacher tries to compel

attention by force, the result is usually not curiosity but boredom:

the bothersome feeling, to paraphrase the psychologist John D.

Eastwood, that occurs when we can’t engage with the information

before us, even if we want to.

Curiosity, by contrast, can be actively promoted in the

classroom: not by demanding attention, but rather by framing

knowledge in terms of digestible information gaps. The simplest

way to do so, familiar to teachers everywhere, is by asking questions

of your students. There’s a reason why the practice of teaching by

posing questions—the so-called Socratic method—has stuck around

for millennia. When it works, it makes learning feel as satisfying as

eating or drinking.

—

Or even consuming harder stuff. One thing that’s so pernicious

about drugs that affect the reward centers of the brain is how

quickly we can develop associations between those drugs and the

sensation of reward.

Fortunately, the same applies to the fulfillment of curiosity. I

sometimes tell this story to my daughter, and she doesn’t always

believe me, but it’s true: On the oil platform, I developed such a

strong association between a sense of reward and the attainment of

useful knowledge that I felt, for the first time in my life, compelled

to learn not by forces outside me, but from within. By the time I

stepped off that platform, my brain felt hungry.

Actually, to be technical, what I stepped off was an icy step on

the platform’s exterior. I twisted my knee badly, and then it was

back to the mainland for me. I recall that long helicopter ride vividly

for two reasons. One: Immediately upon donning my protective dry

suit and strapping in, I regretted drinking water beforehand. And

two: It was on that flight that I realized that I had to go back to

school to pursue an academic career. I needed to learn more—and

faster.

That was the career trajectory that eventually took me to MIT,

where I would get the chance to continue to learn alongside some of

the best minds in my field, mechanical engineering—and also to

learn about learning itself, thanks to my close proximity to

researchers like Kanwisher, Gabrieli, and others working in the

high-rise of cognitive science disciplines.

Systems-level cognitive scientists, in their quest to uncover how,

where, and in what circumstances memories are stored, have

uncovered deep processes that are utterly crucial to the job of every

student. These findings fly in the face of the all-too-common idea

that learning should be a struggle: an ordeal to be surmounted by

force of will. In fact, whether a student is struggling mightily to read

despite dyslexia, or struggling to keep her eyes open in a boring

lecture, effort alone is often not enough to win her the day. For even

highly motivated learners to reach their potential, we have to find

ways to tally the practice of education with the demands of the

systems-level brain. In many cases, the most important thing to do,

practically speaking, is to find ways to promote curiosity.

Any veteran teacher can quickly rattle off strategies to promote

curiosity that work even within the constraints imposed by the

traditional classroom format. Some swear by connecting the

curriculum to students’ existing interests. (This approach can easily

misfire, however, as with the tragically unhip English teacher

satirized in the classic Onion op-ed, “Shakespeare Was, Like, the

Ultimate Rapper.”) Other strategies involve creating information

gaps by means of the Socratic method, or encouraging students to

skim a chapter before reading it in earnest, thereby setting up

questions that only a careful perusal will answer. Still other tactics

lean into the learning-progress theory of curiosity by, for instance,

calling out common misconceptions about a topic before diving in.

But such strategies come with intrinsic limits. Most important,

they only work well for motivated students. And then even if

students are motivated in a general sense like I was as an undergrad

(I wanted to learn but couldn’t make myself curious), promoting

curiosity can present a chicken-and-egg problem, requiring a little

knowledge up front that, though tiny, can still be hard to choke

down.

Is there a more organic way to lead students to drink from the

fountain of knowledge—not through main force, but out of genuine

thirst?

Kanwisher was discussing how MIT’s Building 46 wasn’t a

traditional academic monolith so much as a bridge between levels of

resolution when she stopped to make an important point. “The

other piece not to be left out,” she said, is the suite of labs on the

McGovern side of the building where inquiry above the systems

level takes place. “That is the part of the department where people

actually think about thinking,” she said. Although the systems level

of neuroscience has revealed much about the mechanics of memory

and the states that enable it, there’s far more to learning than

memory alone. And to understand more, I need to climb up higher:

to talk to MIT’s cognitive psychologists.

\*1 Of the non-hippocampal regions damaged in Molaison’s surgery, most, like the

hippocampus itself, are found in the medial temporal lobe, a name that has nothing to do

with time and everything to do with its proximity to your temples. His symptoms,

however, were primarily due to his missing hippocampus.

\*2 Later studies would put too much stock in priming by suggesting that it could be used to

influence behavior outside the laboratory; these findings mostly proved impossible to

replicate. To Gabrieli, however, exploiting priming in this way was never the goal; it was

just a tool for sounding out the substructures of memory.

\*3 The ridges and canyons that give the outside of the brain its wrinkled appearance are

known as gyri and sulci, respectively.

\*4 Calyptra thalictri, found throughout Eurasia.

- IV -

LAYER THREE: REVOLUTION

Brandon McKenzie plowed through the water, pensive. It was

midway through the semester, the final robotics competition for

Course 2.007 was already looming in the calendar, and he was

falling behind. Even now, on a weekday afternoon, Z Liang, Amy

Fang, Alex Hattori, and others were probably honing their designs.

Brandon, meanwhile, was swimming laps: always moving forward,

never seeming to get anywhere.

His brain didn’t switch off when he swam, however. The

backstroke, in particular, allowed him to gaze skyward, watch the

natatorium’s rafters and ventilation ducts slide by, and think about

whatever was bothering him.

Today, he couldn’t decide what was bugging him more, his robot

or his professor, Amos Winter, so he considered both in equal

measure. Earlier in the week he had crossed the first major

milestone en route to the final competition, but he had not done so

with flying colors. He and his classmates had been tasked with

demonstrating their “most critical module” (MCM, in engineer-

speak), the component most directly responsible for earning points

in the competition. This year’s competition would be Star Wars–

themed, prosecuted on and around enormous X-wing fighters. The

team of instructors at MIT’s Pappalardo Lab had outdone

themselves this year and unveiled two identical perfect wooden

replicas of the starships, twelve feet from wingtip to wingtip and ten

from nose to stern.

It is possible, however unlikely, that you’ve never seen a Star

Wars film and so don’t know an X-wing from a TIE interceptor. An

X-wing, unlike some of Star Wars’ stranger spaceships, is

recognizably similar to a real-life, single-occupancy fighter jet, with

the major exception that each of its wings can be made to split open

like the covers of a book, presumably for the sake of combat

maneuverability, to form an overall shape that, from the front, looks

like a squat letter X.

The competition would unfold two students per X-wing. Brandon

and his future adversary would line up on either side of the fighter’s

nose cone, their backs to the auditorium’s audience, with their

robots resting at knee height on a black wooden stage that also

supported the X-wing. The starting bell would sound, then their

robots, operating either under remote control or autonomously,

would race to score points by completing any of a variety of tasks on

or underneath the wooden starship. The most obvious way was to

spin the X-wing’s “thrusters,” tube-shaped objects affixed to each of

the starcraft’s four wings, tucked in close to the central cockpit. In

the Star Wars films, the thrusters function like rocket engines, but

in this case, they more closely resembled spinning jet engines, with

a thick wooden wheel mounted on either end of each thruster,

designed to turn in place. Because there was one thruster per wing

and two wings on either side of the X-wing, each student would

have a crack at spinning both a lower thruster and an upper one.

The faster their robots spun a thruster, the more points they would

earn, with extra points awarded for the upper one, since it was

harder to reach.

To complicate matters, a twenty-five-pound, cast-iron flywheel

was built into each thruster, which would require serious torque to

budge. The motors provided to 2.007 students, meanwhile, were

either high-torque servo-motors, which would turn only slowly, or

high-speed, lower-torque drive motors, not exactly up to the task of

spinning a twenty-five-pound weight. Some students had begun

building gearbox transmissions to solve the torque problem, a

challenging prospect Brandon didn’t relish, because even if he

figured it out, there was still the challenge of manipulating the

thrusters. Two schools of thought had emerged: You could either

drive a wheel somewhere on the surface of the thruster, turning it

by means of friction, or else you could insert a fork of some kind

into the four “buttonholes” sunk into the thruster’s flat face, and

spin it as though gathering up spaghetti. Already, Brandon’s

classmate Z had been observed tinkering with a two-pronged fork in

the lab.

If spinning the lower thruster was complicated, the upper

thruster was especially forbidding, requiring a robot to either extend

up an arm of some kind for a frontal approach or execute a hair-

raising drive behind the X-wing, up a motorized elevator, and onto a

shelf behind the starcraft, where it could approach the thruster from

the rear.

Brandon had set his mind on what seemed to be a simpler plan.

In addition to the thrusters, there were several other ways to earn

points. Protruding from the ground in front of the starship’s twin

wings was a small acrylic stand, and hanging beneath it from their

magnetized hands were three heavy, metallic toy bad guys:

stormtroopers. Robots could earn points by removing these

stormtroopers from their stand and magnetizing them to metal

strips strategically placed throughout the game board, such as on

the underside of the lower wings of the X-wing.

Brandon had consulted with Josh Graves, his roommate and

right-hand man, and they had decided to go after the stormtroopers

with a pincer-like device. That raised problems of its own, however,

such as translating the circular motion of a motor into the lateral

movement of the pincers. Brandon had cut sheet metal into six long

strips and attached them to form three sets of blunt scissors, which

a motor could close by pulling on a length of fishing line. He’d been

excited to show Winter the progress he had made on this device,

which was now officially his MCM.

Winter’s plan for the day was to wander around the lab, spending

about ten minutes with each student as they demonstrated their

work. Brandon was adjusting his scissors at one of the X-wings,

trying to get the device to latch on to a stormtrooper. On the other

side of the X-wing, his classmate Zooey Bornhorst was fiddling with

her own MCM. Winter came over to her first, and soon Brandon was

overhearing sounds of praise. Like Brandon, Zooey was going for

the stormtroopers, but her MCM had no moving parts. Instead,

she’d figured out a clever way to slide a ferrous finger of metal next

to the stormtroopers’ magnets in such a way that pulled them away

cleanly.

Winter walked over to Brandon’s side of the X-wing, where he

was still struggling to get a solid enough grip with his pincers to

overcome the magnets holding the stormtroopers in place. Winter’s

expression was hard to read, but the stream of praise that had

flowed so effusively minutes ago had dwindled to a trickle. Winter

provided some advice: It would probably be necessary to cut a hook

shape into Brandon’s scissors, so they could act less like scissors

and more like insect mandibles—but even then, Brandon would

need not only to latch on to each stormtrooper, but also to pull it

down in order to free up the magnet. “That,” said Winter, frowning,

“adds a layer of complexity.”

Winter moved on down the line, leaving Brandon with his

pincers. Amy Fang had perhaps the flashiest-looking MCM: a giant

wheel meant to rotate the thruster by spinning against its flat face.

Jordan Malone, the computer-aided-design wizard, had built an

industrial-style scissor lift out of laser-cut acrylic parts. The day’s

biggest surprise, however, had come from Z, giggling off to one side.

He’d adopted the spinning-fork method of thruster rotation, but

instead of messing with a gearbox, he’d simply plugged the faster of

the lab-provided motors straight into the most powerful battery

available—the probably-not-explosive lithium polymer battery—

rather than drawing power from the Arduino, which would have

made the motor easier to control but produced a relatively staid

output voltage. Now he held his fork up to the holes in one of the

thrusters and turned it on. In a matter of seconds, the thruster was

rotating at an astonishing twenty-five radians per second. Suddenly,

Z was looking at the possibility of earning a huge number of points

—far more than Brandon or Zooey could with their stormtrooper

strategy, or nearby Ananya, whose arch-shaped robot was struggling

to lift a block modeled after Han Solo’s carbonite prison from The

Empire Strikes Back. Z, it seemed, had discovered what appeared to

be a loophole in the competition, and could barely contain his glee.

Now, a few days later, Brandon swam and thought. He’d met

with Winter at his office, filled with vintage Transformers toys, to

discuss strategies. It had been a confusing experience. Every time

Brandon brought up problems he was having with his scissors,

Winter always came up with a helpful suggestion, but at the same

time, he always seemed to stop short of offering his true opinion on

the overall design. “I felt as if he was just throwing me a bunch of

more complex ways to fix my machine that was just kind of—it was

discouraging, because it felt as if it would be a complete time sink,”

Brandon later recalled. He let out a sigh. If Winter did hate his

design, he was keeping his feelings to himself.

THE INERT KNOWLEDGE PROBLEM

Brandon’s suspicions were correct: Winter harbored little love for

Brandon’s scissor grabber. “That idea had tons of uncertainty,”

Winter recalled later, after the final competition. The mechanisms

involved were “really kludgy, and weren’t going to work well.” But

even if the scissors were simultaneously ineffective and

overcomplicated, Winter couldn’t just go and tell Brandon to give up

on them and try something else. The moment he did—the moment

he rattled off the approaches that would have worked better, which

were manifold—he would have defeated one of the main purposes

of the course: to teach students not just the principles of calculus

and physics and mechanical engineering, but how to think using

those principles. To bring inert lumps of knowledge roaring to life.

It still makes me cringe to think of all the time I spent as a

student, building up piles of inert facts in my head with no intention

of ever putting them to use once I’d puked them out onto a final

exam. But my emotions pale compared to those of my close friend,

the physicist and MIT educator Sanjoy Mahajan, who has made it

his personal mission to revivify inert knowledge, especially in math

and physics, wherever he finds it. To illustrate the problems with

traditional rote learning, he frequently gives an example from

Newtonian dynamics, one of his specialties as a physicist. He asks

his audience to imagine a steel ball falling onto a steel table and

bouncing back up. Neglecting air resistance, what, he asks the

crowd, are the forces acting on the ball at the split second when it’s

touching the table, before it bounces? Most students who have

taken a Newtonian physics course will claim that in addition to the

weight of the ball, the table is also exerting some kind of upward-

pointing, “normal” force on the ball. Usually, they say that this force

is equal to the weight of the ball, since the ball is momentarily

moving neither downward nor upward.

Mahajan rolled his eyes over a cup of decaf tea at the Atomic

Bean Cafe, a hip, brick-walled coffee joint halfway between MIT and

Harvard that has the Kinks and the Replacements on constant, loud

rotation. Raising his voice above the music, he explained how

students at top university after top university get it wrong. “I’ve

asked this question at Olin”—the small, prestigious engineering

college in Needham, Massachusetts—“I’ve asked this question at

MIT, I’ve asked it of the students in Cambridge,” he said, meaning

the one in the UK, “and ninety percent will say the upward force

equals the weight.”

It’s easy enough to prove that wrong. In his presentations,

Mahajan invites a volunteer to place her hand on a table, palm

down. Mahajan then reaches into his bag and pulls out a tennis-

ball-sized rock. First, he places it gently on the back of his

volunteer’s hand and asks if it hurts: it doesn’t. Then he picks it up

and dangles it portentously, high above the volunteer’s hand—which

the volunteer always quickly withdraws in fear. Why, Mahajan asks,

did you move your hand? After all, 90 percent of physics students

said that the only forces acting on a steel ball (or rock) at the

bottom of a downward plunge were the weight of the ball and the

normal force from below—the same as when the rock was resting

peacefully on the back of your hand.

The real problem, of course, isn’t with the volunteer so much as

with the vast majority of physics students. Everyone understands at

a gut level that a falling object exerts more downward force than an

object at rest—several thousand times as much, easily—which is

why volunteers flinch when threatened with falling rocks.

Advanced, successful physics students, however, routinely fail to

connect that intuitive knowledge with the organized, pre-abstracted

knowledge they’ve learned in their physics courses. It’s almost as

though the act of accessing memories created in the classroom

shuts down the experiential part of their brain. To co-opt Woodie

Flowers’s phrase, they have learned physics, but they have not

learned to think using physics.

The issue of inert knowledge crops up across courses of study.

The question of how to coax third- and fourth-year humanities

undergrads to apply strategies learned in their first-year writing

courses, for instance, has become a stand-alone subfield of

educational research. And in physics, professorial worries about

inert knowledge go back at least fifty years. In 1969, J. W. Warren, a

London physics professor, presented 148 of his students with a

series of questions that should have been no sweat, but which were

structured more holistically than the students were accustomed to.

For instance: Instead of asking students to puzzle out the

magnitude of force x acting on a car driving in a circle at such-and-

such speed, he asked them simply to diagram all the forces acting

on the car, and to identify which force corresponded to the friction

exerted by the ground on the car’s tires. Less than a third of

students were able to identify the forces acting on the car, and only

three of them successfully diagrammed the direction of the

frictional force, which should have pointed toward the center of the

circle. (Without such a force, the car would simply slide away, as

though on ice.)

Nearly half a century later, a group of like-minded professors,

including Mahajan and me, posed the same exact set of questions to

students of dynamics at MIT and the Olin College of Engineering. I

wish I could tell you the modern students performed better, but

ours made the same mistakes that Warren’s did in the 1960s, at

essentially the same rates.

If we had failed to fix the inert knowledge problem since the

1960s, it wasn’t for a lack of trying. Western education has changed,

at least on a surface level, considerably since Warren’s study. The

late sixties were boom times for both those seeking to challenge

authority and also those convinced the West was falling behind the

Soviets in science education, and Warren’s study only added

momentum to a well-intentioned if fractious push to shake up

traditional classroom practices. In American teacher-ed schools, this

drive often took the form of freewheeling, Dewey-eyed visions of

education that centered more on students’ professed interests than

on a strict curriculum, and tended to involve more group work, less

reliance on textbooks, a flexible daily schedule, and, where possible,

pacing attuned to each individual student. Depending on which of

these facets took priority, practitioners variously adopted names

like informal, child-based, indirect, project-oriented, and

constructivist to describe their approaches. Despite their internal

differences, it will make sense for our purposes to group these

systems together as “outside-in” approaches, aligned with Dewey’s

outside-in approach to conducting science. These sorts of systems

leaned toward treating both curricula and the learning process as

inviolable wholes, preferring not to over-engineer instruction, but

rather let the student’s natural inquisitiveness lead the way.

Perhaps the most extreme form that outside-in pedagogy has taken

is discovery learning, wherein students, acting like junior Newtons

and Mendels, are tasked with discovering fundamental truths about

the world for themselves.

Whether a given school adopted such changes in any significant

way depended on a variety of factors. Some rewrote their mission

statements with the zeal of converts; others, if my grade-school

experience in India was any indication, remained wax-eared to the

larger movement. At MIT, the trend inspired both research and

instruction, including the revamped and revitalized Course 2.007

(originally called Course 2.70), to which, in 1970, Woodie Flowers

added its now-famous robotics competition. Such a hands-on

challenge, the thinking went, would defibrillate inert knowledge to

life.

Outside-in critics of traditional education, Mahajan explained,

had argued that “ ‘Well, students can’t do.’ ” He sipped his tea. “And

they’re correct.” But doing alone, in the outside-in line of thinking,

wasn’t sufficient as a remedy: The teacher couldn’t just deliver step-

by-step instructions for how to design and execute a complex

project, because then students would only ever learn to paint by

numbers. Rather, students had to carry over abstract knowledge

into real-world practice for themselves. It was for this reason that,

although Winter hinted to Brandon how he might improve his

scissor module, he refrained from telling him to scrap it in favor of a

better strategy.

Of such an approach, “I think that maybe the fundamental axiom

is the teacher is a ‘guide on the side,’ not a ‘sage on the stage,’ ”

Mahajan said.

Even as such strategies spread, however, a countervailing group

of educators began to voice reservations. Some drawbacks were

obvious: hands-on learning could be resource intensive, for

instance, and when schools eschewed such quantitative measures as

grade point averages, student progress could prove hard to track.

But there was also a deeper issue—an issue around which critics

soon coalesced, convinced that the supposed cure for traditional

instruction was worse than the disease.

Mahajan counts himself among them. “I think discovery

learning,” he said—outside-in instruction at its most radical—“is

complete rubbish.”

The fissure between the laissez-faire, outside-in camp and their

opponents comes down to how the two sides interpret research at a

specific level in the cognitive high-rise—the level at which we’ve just

now arrived.

By the late 1950s and 1960s, the gap separating the uppermost

levels of brain science and the lowest levels of psychology were in

some instances beginning to close. This process was, and remains,

fraught with tension—perhaps unavoidably. The research purview of

systems-level brain scientists, though mind-bogglingly complex,

consists essentially of things, not people: neurons, memory, drive

states, and so on. When you zoom your microscope of inquiry out,

however, until you’re operating at a psychological level, something

ineffable slips into your field of view. Suddenly, your jurisdiction

includes not just biological machinery but entire human beings in

all their glory—and with them, all the unanswered head-scratchers

about the human experience that have vexed serious thinkers for

millennia. Closing the gap between brain and psychological

sciences, then, involves sidling up to scorchingly hot philosophical

questions: the nature of human volition, for instance, and even the

nature of consciousness itself.

More immediately relevant to education: The borderline where

brain science meets psychology is also where researchers start

talking less about memory and more about learning. The two words

are not synonymous. Memory entails the mere storage of

information, while learning involves abstracting meaningful rules

and patterns from that information and putting them to work.

Although learning is certainly possible at lower levels in the

cognitive high-rise—the brain’s letterbox, for instance, learns to

abstract the identity of letters from their shapes—it is at the

psychological levels that actionable learning strategies for students

and teachers begin to pop up in earnest.

Both outside-in- and inside-out-leaning education reformers

agree that the way most classrooms today package and deliver

information isn’t working; it results in inert bodies of knowledge.

They also concur that a more user-friendly, less cognitively

obstructive approach to instruction is the key to fixing this problem.

Where they disagree, however, is in how they define “user-

friendly”—a point of ambiguity that arises at the charged point in

the cognitive high-rise where neural activity gives way to thought,

and memory gives way to learning. The result is two separate plans

for overhauling education that, at least at first glance, cannot

possibly coexist.

THE COGNITION SWITCH

The 1950s had been a golden era for the behaviorists, with their

allergy to any mental process between “input” and “output,” but by

the end of the decade, change was in the wind. Across a variety of

fields, researchers had begun prying apart some of the mechanisms

supporting how we think. Across brain science and cognitive

psychology—that is, the subfield concerned with the inner workings

of thought—and with help from sibling fields like linguistics and

computer science, a loose collection of trailblazing scientists kicked

off a new phase in how we think about thinking, later known as the

cognitive revolution.

In terms of education practice, it was the psychological side of

the revolution that broke through first. The genesis of cognitive

psychology was closely tied to the American rediscovery, in the

1950s, of Jean Piaget, a Swiss psychologist some two decades

Thorndike’s junior whose ideas had been all but forgotten in the

English-speaking world.

Today, Piaget is rightly esteemed as one of the titans of

twentieth-century psychology, whose long career not only paved the

way for contemporary, outside-in educational practices but also

brought the research field of child development into the modern

scientific era. His early career is also notable for another reason: It’s

a testament to how different minds can respond differently to the

same stimulus. To E. L. Thorndike and his allies, the first modern

intelligence test, developed by the French psychologist Alfred Binet

in 1905, presented an opportunity to sort learners by their

supposedly innate ability. To Piaget, however, it was a chance to

identify not what separated individuals, but rather what we all had

in common.

Piaget grew up at the turn of the twentieth century in the

Neuchâtel region of French-speaking Switzerland, where he

exhibited a precocious interest in zoology in general and mollusks

in particular. He zoomed through his coursework so quickly, in fact,

that by age twenty-one, he had already earned his PhD but only

begun to find himself. Shortly after delivering his dissertation, he

began a new career in the still-young field of psychology. He studied

in Zurich under the famed psychoanalyst Carl Jung and psychiatric

pathologist Eugen Bleuler, and then accepted a teaching position at

the Sorbonne in Paris. There, he made the acquaintance of

Théodore Simon, the longtime collaborator of Binet, who had died

years earlier.

Soon, Piaget was in the intelligence-testing business. Charged

with standardizing for children a test originally designed for adults,

his job was simply to administer the test orally to the young test

takers and record the number of incorrect answers. He strayed

beyond his brief, however, and in an attempt to understand the

children’s reasoning, followed up their incorrect answers with

penetrating questions of his own, a method that would become a

staple of his long research career.

Children, he discovered, appeared to make the same sorts of

mistakes at roughly the same ages, which unfolded in a somewhat

predictable progression. This suggested the existence of discrete

stages of development that children passed through as they grew up.

The details of these stages, on which Piaget bestowed names like

“sensorimotor” and “preoperational,” have not held up to modern

scrutiny. His underlying assumptions, however, have not only

remained mostly unassailable, but have inspired generations of

further research.

Informing virtually all of his subsequent work was an

observation he made at the very start of his career. Young children,

he discovered, only make childlike mistakes as a result of naïveté,

not an underdeveloped ability to reason. For instance, he realized,

young kids commonly assumed that, say, a dozen pebbles in a pile

would magically increase in number if the pile were spread out over

a larger area. When they discovered that the number of pebbles

actually stayed constant, they often experienced it as a revelation.

In this case and others like it, the most important part of the

learning process was that moment of realization, which Piaget

viewed not as an act of data storage but rather one of invention: the

active creation of a personal rule of thumb about the world. What if,

Piaget reasoned, this sort of creative process is actually how we

assemble the sum total of everything we know? In addition to

fundamental rules of the sort illustrated by the pebbles, this theory

appeared to explain learning via simple observation as well. When

you think back on a visual scene—say, your breakfast this morning

—it will probably appear in your mind less like a perfect photograph

and more like an impressionistic painting, with only a few relevant

details fleshed out. (You might, for instance, recall that you ate

Cheerios, but not how many.) This selective attention to detail

makes perfect sense if you think of learning not as a sequence of

passive snapshots but rather as an active process of fabrication,

adding up to your own personal homegrown model of reality, in

which certain facts are necessarily more important than others.

Such a vision of learning could even explain—and this was

something a later generation of educators would seize upon with

zeal—how some people appeared to improve not just their bank of

knowledge but also their problem-solving and decision-making

skills over time, as they built up representations of raw knowledge

as well as personal theories about how best to act on it.

The sum total of your knowledge, in this model, consisted of

innumerable individual sketches and rules—what Piaget referred to

as schemata, or schema in the singular—assembled into a treelike

whole, with long branches growing out of a trunk of basic

knowledge.

Prior to the late 1950s, Piaget wasn’t so much ignored in the U.S.

as politely entertained—he gave a handful of Ivy League lectures in

the 1920s and 1930s—and then forgotten in a miasma of

behaviorism and disrespect for the supposedly feminine field of

child development.

Then, on October 4, 1957, a tiny white dot passed over the

American night, fraught with implications for the United States’

military security, not to mention its national ego. Paying especially

close attention to Sputnik and its policy aftermath was the MIT

physicist Jerrold Zacharias, a Manhattan Project alumnus whose

work in the field of nuclear magnetic resonance would eventually

lead to the development of the MRI. A year earlier, Zacharias had

secured federal funding to try to find a way to close the perceived

“knowledge gap” separating American students from their Soviet

contemporaries. Now, under the roving eye of Sputnik, such efforts

took on new urgency. President Eisenhower quintupled the

National Science Foundation’s budget, appointed MIT president

James Killian as his first special assistant for science and

technology, and created the President’s Science Advisory

Committee, on which Zacharias sat.

To Zacharias, the influence of behaviorism over U.S. education

was a major cause of the knowledge gap. In an effort to find a new

way to motivate students, he hired a close personal friend, the

Harvard psychologist Jerome Bruner, whose skepticism of

behaviorist thought was so pronounced that, a year earlier, he had

led a psych-department splinter group away from the oversight of

the uber-behaviorist B. F. Skinner.

In 1959, Zacharias convened a conference of psychologists and

research scientists in Woods Hole, Massachusetts, to discuss how to

apply to science education the new findings coming out of the

cognitive sciences. Bruner turned his conference report into a book,

The Process of Education. Unlike most American psychologists, he

had been a strong believer in Piaget’s work for years, and included a

discussion of Piaget’s alternative to behaviorist models of memory.

The book proved a surprise success, selling nearly half a million

copies in four years.

Just like that, Piaget was back on the map, and this time,

America was ready. By 1960, the cognitive revolution was in full

bloom, and its epicenter was Cambridge, Massachusetts. If you’d

stood at the eventual site of the Atomic Bean Cafe, midway between

MIT and Harvard, you couldn’t have heaved a sidewalk brick

without striking a cognitivist breaking new ground. At Harvard,

these included Bruner; his colleague George Miller, who, as I’ll

explain ahead, had begun to plumb the depths (more like shallows)

of working memory; and the psychologist Roger Brown, who was

studying language development in children. At MIT, meanwhile,

you could find computer scientists beginning to think through how

to build a mind from scratch, as well as, crucially, the cognitive

linguist Noam Chomsky, whose scathing 1959 review of Skinner’s

book Verbal Behavior served as one of the cognitive revolution’s

opening shots. Into such a heady cognitivist milieu, Piaget’s

theories fit like a missing puzzle piece.

Mahajan leaned back and glanced around the Atomic Bean.

“Representations have to be built in a person’s cognition and mind.

That part, I think, is unarguable,” he said. The problems with

Piaget’s theories of learning, he said, only arise in the transition

from theory to practice: when one seeks to turn them into “a

philosophy of education.”

The Piaget-inspired pedagogical strategy destined for greatest

controversy was the aforementioned discovery learning, which

assumed that the best way for a learner to add new knowledge to

her schematic tree was not to have it served up by a teacher, but

rather to discover it organically. Teachers, in this model, served as

facilitators of discovery, their sole instructional duty to teach

learning and problem-solving strategies, not actual facts about the

world. The content of school thus became a means to the end of

teaching students to “learn to learn,” as a newly popular maxim

went.

CAMPUS CONSTRUCTION

Teacher-ed programs served as the main, albeit circuitous, route by

which Piaget’s ideas found their way into American educational

practice. Their channel into MIT was more direct, however, and so

they made their stamp here more immediately. And in its way, MIT

soon stamped back.

Piaget’s main ideological vector on campus was one Seymour

Papert, a South African mathematician and computer scientist who

spent four years working with Piaget in Paris before making his way

to MIT. Peering past the massive institutional computers he was

using in the late 1960s, Papert saw ahead to a time when computers

would be cheap and ubiquitous enough that children might want to

learn to code. He developed Logo, a simplified coding language, to

help them do so. “Some think of using the computer to program the

kid; others think of using the kid to program the computer,” he

wrote in 1971, in a prod perhaps aimed at Skinner, who was still

proselytizing his teaching machines a couple miles up the Charles

River. Papert developed the Logo Turtle, an early robot housed in a

transparent dome the size of a halved basketball, to help students

turn the esoteric experience of programming into something

tangible. The Turtle, which predated ubiquitous computer video

displays, was the display: it could drive on top of a large sheet of

paper, drawing geometric designs as it moved. For students lucky

enough to have access to one, the purpose of mathematics changed;

it went from a problem-solving tool to a creative tool.

Today, Papert’s legacy at MIT continues, borne forward into the

smartphone age by his student and longtime collaborator, Mitchel

Resnick.

Resnick stands about six-foot-four and has worn a salt-and-

pepper beard for as long as I’ve known him. When he talks to you,

he leans back in his seat and looks through the lower half of his

eyeglasses with twinkling eyes. He leads MIT’s Lifelong

Kindergarten group, which is dedicated to “designing, creating,

experimenting, and exploring” well into adulthood.

Early one morning in his warm, primary-color-filled office,

before the rest of his team had shown up for work, he examined the

legacy of his intellectual forebears. “Piaget—I think one of his big

contributions was that learners, kids in particular, actively construct

knowledge. It’s not fed to them,” Resnick explained. “And Seymour

totally agreed with that, but he said, ‘And one of the most effective

ways of people constructing knowledge is through constructing

things in the world.’ ”

Seymour Papert meant that quite literally, in fact. To his mind,

the best way to erect a flowering tree of knowledge was to build

objects: in the classroom, in the garage, in a computer. “The

construction that takes place ‘in the head’ often happens especially

felicitously when it is supported by construction of a more public

sort ‘in the world’—a sand castle or a cake, a Lego house or a

corporation, a computer program, a poem, or a theory of the

universe,” Papert wrote in his book The Children’s Machine.

“The act of creating things in the world sparks me to think about

things in a different way,” elaborated Resnick. “And as I think about

things in a different way, it sparks me to create new sorts of things.”

Today, constructionism, as Papert’s philosophy is known, has a

reputation for applying mainly to STEM (Science, Technology,

Engineering, and Mathematics) fields, particularly engineering; but

Papert, who died in 2016, would have disagreed with such a limited

reading of his idea. In fact, the humanities have long relied on

constructionist teaching methods; if anything, the STEM fields are

just now catching up, borrowing from the greatest hits of

humanities education. It’s hard to pass a course in the creative arts,

for instance, without committing an act of creation: a painting, say,

or a musical composition, or a poem. Meanwhile, other fields of

study in the humanities, particularly at the college level, are built

around prose writing, an undeniably creative endeavor.

“The act of writing helps you to organize, express, and share your

ideas,” said Resnick. Indeed, he said, “We want everyone to learn to

write—it’s not only for people who are going to grow up to become

professional writers.” Not only does writing help students learn to

formulate and express their ideas logically, but it also has, at least in

theory, a virtuous social effect. “I think it’s important to help give

everyone a voice,” he said, “to make them feel like they can be an

important contributor to the ongoing things in the society.”

Today, however, many of the visible and hidden rails that guide

our lives are written not in English or Spanish or Mandarin, but in

the language of computers. “For me, learning to code is very similar

to learning to write,” said Resnick. “It’s not just for people who are

going to use it in their jobs, and it’s not just for learning

computational concepts, although it’s good for that. It’s another way

of expressing your ideas and to organize your thinking.”

When Papert made the argument that everyone should learn to

code in his 1980 book, Mindstorms, the idea caught on quickly, and

Logo coding was even made a mandatory subject in UK and Costa

Rican public schools. However, despite its popularity and Papert’s

fervent hopes, the programming language didn’t revolutionize

education. Logo itself was part of the problem. Papert intended the

language to be easy to learn, but its syntax was still reasonably

difficult, which turned off beginner students and instructors. As a

result, even as computers began to pop up in classrooms and

computer labs in the 1980s and 1990s, coding literacy failed to take

off. Instead, a different sort of computerized diversion gathered

steam: educational computer games, most of which functioned as

glorified content-delivery systems not so different from Skinner’s

teaching machines.

“Little by little the subversive features of the computer were

eroded away,” Papert wrote. “The computer was now used to

reinforce School’s ways.”

The promise and shortcomings of Logo stuck with Resnick,

however, who earned a computer science PhD at MIT under Papert

and soon began conducting research of his own. Resnick began by

tinkering with Logo, taking it in new directions that included a hit

retail product, LEGO Logo, which allowed students to control Lego

robots using Logo programming. It was highly engaging—but any

disinterested observer would have to admit that the Lego side of

things was more fun than the programming. That sparked an insight

in Resnick: Perhaps the rewarding, intuitive act of snapping

together multicolored blocks could itself be replicated on the

programming end.

The programming language he and his team developed to make

this possible is called Scratch. Instead of a finicky text-based

language, Scratch allows users to code using simple, block-shaped

visual elements. Best of all, those blocks of code are set up, as a

default, to control the movements of characters and objects in

animated videos, meaning that brand-new users can walk away

from their first Scratch coding session with a funny cartoon under

their belt—typically, of a cat dancing across the screen. As of this

writing, Scratch is within striking distance of the scale Papert

originally envisioned for Logo, with 30 million registered users on

its website. Perhaps the program’s most important endorsement,

however, is that learners use it not just when assigned, but also in

their free time—my daughter included—and often in pairs and

teams. “I sometimes say that the ultimate goals of what we’re trying

to do in all of our projects is help people learn to think creatively,

reason systematically, and work collaboratively,” Resnick said.

These sorts of aspirations might seem uncontroversial, but

beneath them still runs the cold current of Seymour Papert’s more

subversive ambition: to change our inherited rules of education.

One thing that bothers Resnick in particular about the Thorndikean

status quo at school is its reliance on letter and number grades for

the purposes of sorting students. “I would certainly be aligned with

reducing the importance of grades,” he said. “At MIT, as you might

know, the first semester there’s not grades. And I would extend that

further.” At the Institute, most of the faculty acknowledges the

grade-free initial semester as a good thing, a mental health boon for

students at a delicate phase of their development. There is still

plenty of internal pushback, however. Resnick said that one physics

professor who teaches juniors told him that because first-year

students were deprived of the motivating force of grades, they

eventually turned up underprepared for his class. Resnick thought

that he was framing the issue the wrong way. “If there’s an MIT

student who isn’t paying attention and trying to learn things

freshman year because there aren’t grades,” Resnick said, growing

grave, “that student shouldn’t be here. That’s a real mistake that

MIT made, to admit a student who’s only motivated because of

grades.”

The idea belongs to a time-honored line of outside-in thought.

Behind every number or letter standing in for a student’s potential

lurks an undeniable, tautological flaw: Put simply, such metrics

don’t measure what they don’t measure. Consequently, it’s

impossible to know how many promising students exist around the

world whose grades and test scores only obscure what they’re really

like as learners. Or worse, perhaps grades, test scores, and the

classrooms that seem to revolve around them actively prevent

certain students from getting excited about learning. A broad shift

toward outside-in, project-based instruction, including MIT’s

homegrown brand of constructionism, might offer students new

ways to prove themselves, while giving them the chance to discover

their true passions. Only then, Resnick said, “will they be willing to

put in the hard work that’s necessary to be really successful.”

Adopting constructionism and its fellow outside-in approaches,

in short, seems like a no-brainer: They provide a welcome injection

of motivation, contextualization, and activated knowledge into an

education system in dire need of all three—plus, as a bonus, a more

forgiving way of thinking about the educational winnower. There’s

just one problem: The murmurs from the growing and increasingly

influential camp of education researchers who insist that outside-in

strategies do not support the cognitive processes necessary for

learning, and may even smother them.

INSIDE-OUT THINKING STRIKES BACK

To talk to advocates of outside-in education like Resnick, the work

of converting their ideas into classroom practice is still only

beginning. (After all, grades still exist.) To hear inside-out thinkers

like Mahajan speak, however, the exact opposite would seem to be

true. Yes, old-school, traditionalist teaching still prevails, but

everywhere you look, outside-in reformers seem to be slipping their

assumptions into the curriculum and, despite their good intentions,

systematically and kindheartedly obstructing learning.

By way of an example, Mahajan brought up how his daughter

was taught to read at a local Cambridge public school.

“All across America,” he said, “kids are read to and given lists of

words to memorize,” a strategy that is meant to make learning to

read as natural as learning to speak. This approach got its start in

the “Whole Language” movement of the 1980s, which eschewed

traditional, phonics-based strategies like breaking words down into

small parts and “sounding them out.” Rather, the thinking went, in

the same way that children naturally map the sounds of vast

numbers of words onto their meanings just by hearing and speaking

them, perhaps they could replicate that feat with written words if

given enough of them to look at. By the late 1980s, Whole Language

was spreading like spilt milk.

It was, in retrospect, an unmitigated failure, for reasons that

became evident only in the wake of the brain research discussed in

the prior chapter. The brain, it turned out, is innately wired to

recognize speech but not written language, and so it’s far easier to

learn the former through exposure alone. Evidence supporting

phonics as the superior tactic began to mount as early as the mid-

1980s, and in 1996 the Whole Language movement received a

dollop of bad news that it could no longer ignore: California, which

had gone all in on Whole Language, had become the worst-

performing state on standardized reading tests.

“I realized it was a total disaster,” Mahajan said. “My daughter,”

who had been part of a Whole Language–inspired reading program,

“couldn’t read ‘dog.’ She’s trilingual! She couldn’t read ‘dog’ at age

seven.”

For those looking to disprove the utility of discovery learning,

the collapse of Whole Language provides a striking but narrow case.

A broader line of criticism came in the form of a 1985 study out of

New South Wales, coauthored by the educational psychologist John

Sweller.

Here’s a pop quiz: One group of students works at solving

algebra problems. A second group doesn’t solve these problems

themselves, but instead studies “worked examples”—that is, algebra

problems that have been solved correctly ahead of time, with the

intermediary steps spelled out. When presented with a new set of

algebra problems to solve, which group fares better?

Surprisingly enough, according to Sweller’s study, it was the

worked-example group who prevailed, despite having logged less

time practicing problem solving. Similar results were replicated

again and again in the 1980s and 1990s, mainly in math-related

fields including statistics, geometry, and computer programming.

These findings rankled outside-in partisans, who had long argued

that classroom time and energy was better spent on problem-

solving strategies than domain-specific minutiae. Perhaps more

troubling, however, was the conclusion drawn by Sweller and his

allies that general problem-solving skills are essentially

unteachable, like learning to walk or speak one’s native language. If

true, all that time outside-in educators and their students had spent

on complex challenges in hopes of developing general problem-

solving abilities had been time wasted.

Or worse: Perhaps all that problem-solving practice had actively

impeded learning. To find theoretical support for this idea, Sweller’s

camp had only to look back a few decades to one of the foundational

studies of the early cognitive revolution, The Magical Number

Seven, Plus or Minus Two: Some Limits on Our Capacity for

Processing Information, by Harvard’s George Miller. The study was

the first modern probe into what became known as working

memory or working attention, an extremely ephemeral category of

memory that corresponds to essentially all the information you’re

consciously aware of at any given moment. Information temporarily

stored in working memory has two possible fates: either longer-

lasting storage in short-term memory (and possibly long-term

memory down the road), or else quick forgetfulness. When they’re

fully concentrating, Miller determined, most people can recite back

roughly seven “chunks” of data from their working memory—a

“chunk” being a highly subjective thing. For instance, the number

2001 would occupy just a single chunk for any fan of Stanley

Kubrick, while the number 7845, chosen at random, would demand

a chunk for each digit.

In 1988, Sweller fired off an article that chilled the ventricles of

the outside-in camp. What if, he wondered, the lackluster

performance of problem-solving students could be explained by the

ineluctable limitations of their working memory? According to

cognitive load theory, as he dubbed it, the cognitive demands of

thinking through how to solve problems occupied critical slots of

working memory that could be put to better use. During the

trickiest moments of studenthood, he reasoned, it would be better

to have all cognitive hands on deck, not occupied working their way

through unnecessary puzzles. “There seems to be no clear evidence

that conventional problem solving is an efficient learning device and

considerable evidence that it is not,” he wrote.

The findings provoked a fractious debate that rages still in the

pages of education and psychology journals. Only very recently,

however, have neuroscientists begun to satisfactorily explain the

mechanisms underpinning cognitive load.

To explain, let’s take a trip back to MIT’s Picower Institute. Back

in the 1950s, Harvard’s George Miller had suggested that human

working memory could maintain as many as nine chunks of data,

but a series of follow-ups had thrown cold water onto that number

and shrunk it down to four. In the 2010s, the Picower researcher

Mikael Lundqvist came up with a plausible insight as to why.

Appropriately enough, he had a four-digit office number, which

necessitated constant mental recitation on the elevator ride up to

speak with him.

The fleeting nature of working memory may not be a limitation

of cognition so much as a feature, Lundqvist explained. After all,

you want the stuff of conscious thought to flow freely, not get stuck

on points for long periods of time. The main question concerning

the “how” of working memory, then, is what makes it so ephemeral.

As in short-term and long-term memory, scientists believe working-

memory representations to be encoded in assemblies of neurons,

held together by patterns of strategically strengthened or weakened

synapses. What, mechanistically speaking, allows working-memory

cell assemblies to build up their synaptic patterns in mere moments

and wipe them clean just as quickly? For a long time, scientists

believed that your prefrontal cortex—the site of working memory—

holds on to its representations by maintaining a consistent buzz of

activity in the cell assemblies corresponding to the items in your

thoughts (that is, right until your attention wavers, and the action

shifts to a different group of neurons).

In 2011, Lundqvist was working on his PhD in his native

Stockholm, using computers to model working memory, when he

hit upon something new. “Instead of using consistent spiking, I

used synaptic waves to store memories,” he said. In such a model,

the chunks preserved in one’s working memory would be preserved

not all at once, as previously thought, but one at a time.

Lundqvist has a muscular frame and shoulder-length blond hair,

and with his Scandinavian accent, he could almost be confused for

someone out of a Norse saga. Only his eyes give away the sleep-

deprived research scientist in him. Since joining Earl K. Miller’s lab

at MIT, he has been putting in long hours to get his model right—

and in a far trickier study system than computers. His data now

come from the brains of a pair of monkeys, outfitted with arrays of

electrodes that tell Lundqvist when tiny regions of the prefrontal

cortex are active. This technique is more invasive than an fMRI, but

fMRI scanners can only describe neural activity on a second-by-

second basis, while the electrodes are accurate down to the level of

milliseconds. A series of these monkey studies have now returned

results supporting Lundqvist’s burst-firing model.

The difference between a continuous model, with its incessant

spiking, and the burst-firing he proposes may seem subtle; but the

burst model provides the most enticing explanation yet for working

memory’s inherent limitations. Imagine if the four available chunks

of working memory were a four-word message written in wet sand

at the beach—SANJAY SARMA IS HERE—under constant threat of

erasure by crashing waves. In the old model, every letter of those

words is refreshed simultaneously, as if by magic. In Lundqvist’s

new model, by contrast, it’s as though the only way to maintain the

words is to retrace them bit by bit, with just a single index finger. If

I grow greedy and try to add a fifth word to the end of the message

(SANJAY SARMA IS HERE TODAY), I might not finish in time to rush back

and preserve the first word from the onrushing waves. Soon

enough, I’m back to a four-word message, albeit a new one: SARMA IS

HERE TODAY . This theoretical “refresh rate” limitation, as Lundqvist’s

team refers to it, provides a strong explanation for why, every time

you add a new chunk of information in your working memory,

you’re likely to lose an older one.

LEARNING, APPROXIMATELY

It is possible to plumb working-memory capacity using softer-edged

metrics than chunks, such as the sheer length of a verbal passage

someone can repeat, or the fidelity with which they can replicate an

image. Using such strategies, researchers have shown working

memory to be both highly variable and correlated to measures of

general intelligence. One upshot is that whenever something clogs

up working memory, your all-around problem-solving abilities take

a hit. Certain disordered conditions, including schizophrenia and

ADHD, can interfere with working memory. Relatively temporary

intruders, too, can get in the way. One particularly pernicious

example that I’ve touched upon occurs in stereotype threat, when

distracting thoughts related to such factors as gender, race, and

socioeconomic status eat into working memory and depress

students’ test scores.

The wrong sort of instruction design, the inside-out camp

argues, can only magnify such issues. When you’re working on a

complex problem, Mahajan explained, “most of your memory is

filled up with ‘search’ ”: the act of running through hypothetical

courses of action, seeking the one that will lead to a desirable

solution. “You think to yourself: ‘Well, what do I know, where do I

have to get? How far away am I?’ ”

Learning via worked examples, instead of solving problems for

yourself, is one potential way past such working-memory

roadblocks. The inside-out faction also endorses “overlearning”

certain facts, like the multiplication tables, so that summoning up

those facts during problem solving becomes undemanding.

Mahajan has a different trick. He is, it turns out, one of the

world’s best estimators. Once, after a colleague of his was issued a

large, confidential settlement during some legal proceedings, a

journalist asked Mahajan to estimate the size of the cash award.

Mahajan’s highly educated guess was so close to the actual number

that the issuer decided someone must have spilled the beans, and

sued.

Mahajan’s feat should have come as no surprise, however, since

he literally wrote the book on approximation (his preferred term of

art), Street-Fighting Mathematics. The title gives a fair sense of his

approach to solving complex problems: First do a quick-and-dirty

run-through of the problem, complete with an approximate answer,

and only then aim your full working memory at the actual task of

solving it. This shoot-first-ask-questions-later approach works not

just for STEM problems, he said, but even for writing. “You have to,

by hook or crook, write a completely shitty first draft,” he said. “It’s

going to be very, very approximate,” but then, on your next pass,

with more working memory freed up, you can make it intelligible.

One thing worth noting about Mahajan’s problem-solving

strategy is that it is, in fact, a problem-solving strategy, and

therefore a departure from the most extreme inside-out position,

which holds that education should consist solely of content, not

process. What Mahajan teaches is process as content: a strategy for

how to direct your thoughts that is not so different from how a

coach advises an athlete to move her body.

In fact, the sometimes-imperfect control we wield over our

thoughts appears to have real commonalities with our oversight of

our bodies. The bursts that Lundqvist has detected moving through

monkeys’ prefrontal cortices are close, timing-wise, to the speed of

the fastest possible actionable information flow in the brain—“on

the border,” he said, of “the speed of thought.” And how might

conscious thought control the contents of working memory? Here,

too, Lundqvist’s model holds tantalizing hints. We can’t say how

volition arises in the brain, or even if we truly have free will over

our thoughts and actions. We do, however, know that the patterns

of neural activity that occur when you create a working-memory

representation are suspiciously similar to the patterns that arise

when you decide to, say, move your arm.

The key is the important neural phenomenon of brain waves:

electromagnetic peaks and troughs that correspond to the massed

activity of large numbers of neurons working in concert. In the case

of your control over your limbs, there is a sort of holding pattern,

known as a beta wave, that prevails in the motor cortex when

nothing much is happening. It appears to act like a wet blanket,

inhibiting unwanted activity, and must be removed if you want to

use your arm. With the wet-blanket beta waves out of the way, a

series of high-frequency gamma waves arrive that correspond with

arm movement. Curiously enough, these come in bursts remarkably

similar to those Lundqvist has observed in his working-memory

studies, which likewise appear to be held in check by a wet-blanket

beta-wave state. The theoretical implications of such similarities are

remarkable: the same volitional process that allows you to control

your limbs may also grant you control over the flow of your

thoughts.

“The dynamics and everything else looks very similar between

the motor cortex in movements and the prefrontal cortex in abstract

thoughts,” he said. “But it’s still open to debate.”

I appreciated Lundqvist entertaining such questions, but perhaps

what I appreciated most was how he was willing to fly near

neuroscience’s version of the sun: the question of volition itself.

“Where the volition actually is, is like the ultimate question,

right?” he said. “Is it just due to the reinforcement learning—that

we learn to recognize the right situation to do something, and it

looks to us like it is volition? Or is it…?”

He trailed off, perhaps feeling his wings grow warm.

—

The inside-out versus outside-in debate comes down to similarly

hot topics. A book from 2009, titled Constructivist Instruction:

Success or Failure?—the cover depicts a pair of debate podiums—

valiantly attempts to give each side a fair chance to respond to one

another. Instead it quickly devolves into both passive aggression

and speculative arguments over whether problem solving is a skill

that can be taught, and whether learners actually have volitional

control over their working memory. Like geopolitical rivals claiming

mineral rights all the way down to the center of the Earth, it can

sometimes feel like the two sides are trying to split up the cognitive

sciences beneath their feet.

It would almost be surprising, however, if, in our ascent up the

cognitive science high-rise, ideology didn’t rear its head at the level

of cognitive psychology. Both sides want to make education better,

but once your scope of study includes human beings in their messy

entirety, you inevitably run into questions like Better how? Better

for whom? Should students follow their own impulses in

determining what to learn, or should they learn to take strict control

of their own thoughts and stick to topics their instructors deem

important? As we continue our journey upward—and then out into

the wider world, where the cognitive science of learning gets applied

—such fractures will persist: an unavoidable, unignorable feature of

any future educational landscape.

But that’s no reason to give up. In the wise words of Luke

Skywalker, Jedi Master:

Breathe.

Just…Breathe.

Back in MIT’s swimming pool, that was what Brandon was trying

to do, even as visions of stormtroopers, Han Solo, and X-wing

fighters floated unbidden through his working memory. Star Wars,

he realized, had begun to take on stressful connotations that he

wasn’t sure he appreciated. The team began a new drill: backstroke

flip-turns, the disorienting, high-speed technique swimmers use to

change direction in a race. The plan was, as with those

multiplication tables, to overtrain the maneuver until it became

truly second nature, and Brandon found his mind pleasantly

occupied by the activity, more cognitively demanding than laps.

From the surface, the technique looks like a frenzy of activity, and

yet, Brandon found himself in a state of clarity that had been

eluding him all day.

Indeed, sometimes there is order to be found in seeming chaos.

It’s a lesson we all learn starting in infancy, as we strive to abstract

meaning from the cacophonous sounds and sights and smells that

surround us. And, appropriately enough, it’s a lesson adults, too, can

take away from the seemingly disorganized learning behaviors of

babies and young children. No one on campus understands this

better than Laura Schulz, a cognitive psychologist who studies the

deceptively rigorous logic that youngsters employ to make sense of

the world.

In the years since Bruner reintroduced Piaget to America, Schulz

explained, his ideas have gone through some changes. “Piaget’s

stage theory, of course, collapsed,” she said, leaving behind only its

most foundational assumptions. In the mid-1980s, a new, more

rigorous theory began to take its place, which likened children to

tiny scientists, an idea John Dewey might have welcomed. As

Schulz’s doctoral advisor and frequent collaborator, Alison Gopnik,

has written: “The basic idea is that children develop their everyday

knowledge of the world by using the same cognitive devices that

adults use in science…That is, they develop theories. These theories

enable children to make predictions about new evidence, to

interpret evidence, and to explain evidence.” This idea, fittingly

named the theory theory, provides a compelling explanation for

how we incorporate new data into our existing trees of knowledge.

When evidence comes in that warrants a modification to an existing

theory, a learner must add to the original, change it, or, in some

cases, jettison it altogether in favor of a new explanation. As Schulz

and her collaborators have shown, when children encounter

evidence that defies their personal theories (often arriving in the

form of deceptively designed toys), a concerted exploratory session

often follows, in which they try to suss out what’s going on. This

outcome fits hand in glove with the learning-progress theory of

curiosity discussed in the prior chapter. Not only does surprising

information trigger the drive state of curiosity, but also, at the level

of conscious learning, it transforms passive observers into de facto

scientists.

Often, however, perplexing new information doesn’t come with

readily discoverable explanations attached. Happily, our brains

appear to have evolved to deal with such contingencies remarkably

efficiently, starting in infancy. Babies, it turns out, interpret events

using not just a parsimonious approach, but often the best possible

approach given the limited data available to them, similar to what

statisticians refer to as Bayesian reasoning.

In one study of the hundreds that support this work, Schulz and

a graduate student systematically played with deliberately broken

toys while babies watched, with their mothers close at hand. When

you’re a baby who wants to play with a toy that’s not working, your

world shrinks down to just two options: try to figure the toy out, or

hand it to an adult. Depending on their observations of how Schulz

and her research partner fared with the toys (Did it always work for

one of them but not the other? Or did it sometimes fail to work for

both of them?), babies strategically decided whether to experiment

with the toys themselves, or pass them directly off to Mom. The

upshot was remarkable: In the face of extremely sparse

information, the babies routinely made the optimal choice. They

were acting, then, not just like tiny scientists, but tiny statisticians.

And although this innate skill may be harder to observe in the

everyday life of adults, in part because the pile of statistical data

we’re constantly integrating is larger and more complex, there’s no

reason to believe we stop adding to our tree of knowledge using

these same principles. Such statistical reasoning may, in fact, turn

out to be the glue holding together the theory of mind Piaget

proffered early in the twentieth century.

You might reasonably assume that, given such strong support for

Piaget-aligned models of learning, Schulz would also endorse

outside-in education practices, but here she steps back.

“I don’t think we’re there yet,” she said. On one hand, “there’s no

way you could learn calculus by discovery,” but on the other, “we

want engineers who will build things,” she explained, and that calls

for a certain amount of learning by doing. As we ponder how to

educate as many people as possible, as effectively as possible, it’s

clear that we’ll need elements of both approaches. We need a wider

tolerance for diverse student motivations and interests, as well as

the powerful ability of outside-in pedagogy, when used correctly, to

make the dusty skeleton of inert knowledge jump out of its coffin

and dance. However, we also need to marshal our resources—money

and time, yes, but also students’ cognitive resources—to teach

useful, hard knowledge. And so we ignore the potential benefits of

inside-out instruction at our peril.

The field of education cannot wait for the perfect answer. We

need to integrate multiple viewpoints in real time, and to update

that mixture as new evidence rolls in. The best response to the

fractured state of educational psychology, fittingly enough, is not to

take sides—but it’s not to seek a haphazard compromise, either.

Rather, we must adopt a Bayesian-style approach. As a young child

behaves like a scientist in constructing her model of the world, we

scientists and educators must establish a working theory of what

works best in educational practice, while remaining open to

changing it as needed.

Hard at work in MIT’s pool, Brandon McKenzie had been

flipping, setting his feet, and launching off the concrete wall for

what seemed like hours when he suddenly figured out what to do

about his robot. Was he upside down or right side up when he

changed his mind? Was his decision-making process truly

volitional, or the product of environmental cues, or perhaps the

result of a complex interplay between his working and long-term

memory? Despite the remarkable advances now being made at all

levels of cognitive science, it’s still impossible to answer these

questions. Nevertheless, by the time he climbed out of the water,

something was different. His mind had changed; his thoughts had

settled. Starting tomorrow, he would focus on spinning the X-wing’s

thruster—even if it meant scrapping everything and starting over.

- V -

LAYER FOUR: THINKING ABOUT

THINKING

Sometimes I like to think about the laws of learning as a map of a

mysterious sea. At the dawn of the twentieth century, E. L.

Thorndike described some of its most significant geographical

features, and ever since, generations of cartographers have

attempted to add detail and, as needed, correct his mistakes. There’s

just one problem: For those who have to actually ply these

treacherous waters—learners and their teachers—it’s not clear

which faction of modern cartographers to trust. On one hand, you

have inside-out maps created using mechanistic models: “Thanks to

what we know about coastal geology, there should be dangerous

submerged rocks here.” And on the other hand, you have outside-in

maps, based more on practical observations: “Ships that head out in

this particular direction often never return, so that must be where

the dangerous rocks lie.”

Both strategies have steered learners astray in the past. It was

the outside-in impulse, for instance, that led many school districts

to experiment with Whole Language. The story remains a

cautionary example of how ignoring the nitty-gritty of brain

function can lead to pedagogical ruin.

But inside-out thinking, too, can lead to missteps. In 1983, the

Harvard psychologist Howard Gardner, observing that brain damage

due to a stroke or other trauma can interfere with, say, reading, but

leave numeracy and other abilities untouched, began arguing that

the brain has not one overarching intelligence but rather many

separate, domain-specific intelligences. This multiple intelligences

theory remains, to this day, a strong, well-supported indictment

against the very idea of general intelligence. As Gardner has put it,

IQ tests may put too much weight on certain abilities simply

because they’re easy to measure: a case “of the man looking for his

dropped car keys underneath the street lamp because that is where

the light is.” His alternative theory, inspired by mechanistic ideas of

how the brain works, served as an inside-out update on older inside-

out thinking.

To Gardner’s dismay, however, a group of true believers soon

took his theory too far, trotting it out as evidence of what became

known as multiple “learning styles.” This noxious idea, which holds

that most students require specialized education media depending

on their supposed brain makeup, lingers zombie-like in education

culture despite a wealth of evidence against it. I still routinely

encounter students claiming to be “auditory” or “visual” or

“kinesthetic” learners. Perhaps they do possess certain relative

aptitudes—clinical psychologists, after all, routinely invoke granular

intelligence assessments in their diagnosis of specific learning

disorders—but that doesn’t, and shouldn’t, change my classroom

approach. Every large-scale review on the subject has shown that

matching the delivery of educational content with students’

preferred learning styles fails to produce any measurable beneficial

effects, and may even hurt long-term retention of knowledge.

Also to be laid at the feet of neuro-minded, inside-out reformers

is the myth of “right brain” and “left brain” dominance, which holds

that certain students are more creative or logical depending on

which hemisphere prevails in their thought, in the same way that

most people are right- or left-handed. This notion can be traced back

to the nineteenth century, but received a major boost in the 1960s

thanks to the crude-in-retrospect procedure of surgically separating

patients’ hemispheres in hopes of curing epilepsy. This practice

revealed that verbal language couldn’t be summoned without input

from the left hemisphere, but in the years since, fMRI research has

shown that almost all cognitive tasks invoke both hemispheres to

some degree. In any case, if someone appears to be more creative or

more logical, there’s no reason to assume that their proclivity arises

at the level of gross brain structure and not at a higher,

psychological level. The concept of right-versus-left-brain

dominance may still be marginally useful in some cases, but only as

a metaphor.

There exist other neuromyths, such as the false notion that we

only use 10 percent of our brains. (Modern-day inside-out thinkers

bear no blame for this one; it can be traced all the way back to

William James.) In fact, even in the Whole Language debacle, for

which outside-in logic bears most of the culpability, inside-out

partisans also had a small role to play.

In the late 1980s and 1990s, teachers entered into a tempestuous

romance with a practice then known as “neuroeducation.” The idea

was built around new research into childhood brain development.

Kids’ synaptic connections, it turned out, increase in raw number up

until about age ten, whereupon the brain commences a years-long

synaptic “pruning” routine via a mechanism that is essentially the

opposite of LTP. This process molds the brain into its adult

configuration by one’s early twenties, when it delivers the finishing

touches to the prefrontal cortex. This region is highly involved in

executive function—not just working memory but also attention,

emotional regulation, and staying on task. I’ve always thought that

its laggardly development must explain some of my behavior at

university.

If the years between birth and age ten were prime time for

synaptic development, the neuroeducation reasoning went, then it

was imperative to flood youngsters’ sensory worlds with data-rich

stimuli before it was too late. “With the right input at the right

time,” a Newsweek writer opined in 1996, “almost anything is

possible,” but “if you miss the window you’re playing with a

handicap.”

There remains some truth to the idea that certain types of

learning are easier to pull off during certain critical periods in

development, verbal language learning chief among them. But in

the mid-1990s, so magical did some consider the period of early

synaptic growth that multiple U.S. states enacted legislation devoted

to such sensory-enriching schemes as the playing of classical music

within earshot of young children, based on a since-debunked idea

that mere exposure to Bach and Mozart would lead to improved

spatial reasoning capabilities down the line. This practice was as

harmless as any other placebo, in the sense that it only caused

problems when it got in the way of better-substantiated methods.

Which, indeed, was exactly what happened in the case of Whole

Language. With the magic period of synaptic creation backing the

claim that kids could somehow make sense of words on the page if

only they saw enough of them, lawmakers and school boards signed

on. The effect, in some states, was a generation of students that

lagged far behind their counterparts in reading.

By the mid-1990s, however—even before the problems with

Whole Language were widely acknowledged—neuroeducation

skeptics were arguing that educators should think twice before

making a leap straight from brain science to educational practice.

“Cognitive psychology is a much better bet” than neuroscience,

wrote the Washington University cognitive psychologist John T.

Bruer, in the most important document of what came to be known

as the “neuroskepticism” movement. “Currently, the span between

brain and learning cannot support much of a load.” Instead, he

suggested, for brain research to contribute to successful educational

practices in the future, it would be best if it were to follow an

“indirect, two-bridge route,” first pausing for verification at the level

of cognitive psychology before continuing along to the classroom.

That’s perhaps a viable pathway for some inside-out thinking to

find its way into useful educational practice. But then again, it still

doesn’t account for the fact that even the most fair-minded

educational psychologists can cherry-pick supporting neuroscience

research when it suits their purposes, which can lead to fiascos like

Whole Language.

Happily, there is another way. We can strategically integrate

inside-out and outside-in approaches by looking back through the

history of the cognitive revolution for psychological theories that

both update Thorndike’s laws of learning in significant ways while

also remaining plausible according to the findings constantly

coming out of neuroscience. One such theory of learning does, in

fact, stand out. Its key insight is as surprising as it is simple: The

secret to better learning may be better forgetting.

THE POWER OF FORGETTING

Over the decades, the vast majority of updates made to Thorndike’s

laws have had to do with his law of effect, which describes how

memories are stored in a web of associations. His law of exercise,

which has to do with forgetting, has received far less attention,

perhaps because most people, Thorndike included, have long

considered forgetting to be nothing more than the loss of memory.

Thorndike’s thesis was simple: Memory decays as a function of

time elapsed since it was last accessed. That the reality was far more

complicated soon became apparent, however. In 1932, the Missouri

psychologist John Alexander McGeoch asked study subjects to

memorize random pairs of words: Please associate the words “cat”

and “peanut,” so that whenever I say “cat,” you say “peanut.” The

simple task became measurably more difficult when, in the interim

between learning and recitation, McGeoch presented his subjects

with confounding word pairs: cat and glasses, or cat and typewriter

—which turned out to make remembering the original pairs far

more difficult than Thorndike’s time-based model of decay would

have predicted.

McGeoch’s explanation changed the very meaning of forgetting.

Study subjects, he argued, failed to remember cat-peanut not

because that memory was erased outright, but rather because other,

competing memories got in the way. Soon, interference, not disuse,

became the leading explanation for forgetting, and this came with

profound new implications for what constituted a memory.

Suppose a memory is an old house, deep in the woods. If

interference, not disuse, had made it inaccessible—say, vandals

blazed decoy trails leading away from the main access trail—that

didn’t mean the house disappeared. It was still back there, just

inaccessible at the moment. Many researchers (including even B. F.

Skinner) began to consider the state of such access trails and the

state of the memory itself—the house—as two wholly separate

questions. Different researchers over the years gave them different

names, but the ones that stuck are the terms “retrieval strength”

and “storage strength,” coined by the cognitive psychologists Robert

and Elizabeth Bjork. As Robert succinctly puts it: “Storage strength

is how well learned something is; retrieval strength is how

accessible (or retrievable) something is.”

When an item has low storage and low retrieval strength—say,

something you can’t remember from a long-ago class to which you

never gave your full attention—it’s not much of a memory at all.

Something recently learned and of temporary importance,

meanwhile—say, Mikael Lundqvist’s office number—has high

retrieval strength, but low storage strength, which means it is

temporarily accessible but readily forgotten. There are also items of

memory with high storage strength but low retrieval strength: The

name of that melody running through your head, or perhaps your

childhood best friend’s phone number, which you can no longer

recall. You might not be able to remember it in the moment, but

given the right cue, the memory would come flooding back.

Finally, a memory with both high storage and retrieval strength

would be something you know well and can easily retrieve at will:

the name of the first American president, say, or your birthday. Or

perhaps the name of someone who changed your life with an act of

unexpected generosity.

A physics-turned-math major from the University of Minnesota

with a John Wayne vocal rhythm and abiding love for the game of

golf, Robert Bjork joined the young field of mathematical

psychology in graduate school. He had put in one graduate year at

Minnesota when his advisor, David LaBerge, told him that the

field’s major figure, William Estes, was moving to Stanford. Bjork

was an impressive student who held great promise for the

Minnesota program, and yet LaBerge urged him to move to

California anyway. “I mean, it was so much in my interest and so

much against his own interest. It’s just kind of amazing,” Bjork later

recalled.

Estes, meanwhile, had been a disciple of B. F. Skinner’s prior to

the outbreak of World War II, when Estes was sent to serve in the

Pacific theater. During the war, according to the story Bjork heard,

family members back home had sent Estes books to read during his

downtime, but there were strict weight limits on what they could

send, and he devoured the books far faster than they came in.

Frustrated, he wrote home and asked for a book on mathematics.

“He wanted to learn more anyway,” Bjork said, plus there was an

added benefit: A serious math book would take a long time to read.

Estes returned at the end of the war with new mathematics

knowledge in tow, and went on to help found the field of

mathematical psychology and the journal of the same name.

Mathematical psychologists attempted to model simplified

learning brains, a line of work that formed a front of its own in the

cognitive revolution, and which ran in parallel with the sort of

computational research Seymour Papert and others were

undertaking at MIT in the 1950s and 1960s. By 1966, Bjork, now

under Estes’s wing, found himself feeding punch cards into one of

Stanford’s handful of mainframe computers, trying his best to make

a mathematical model of learning, known as a Markov chain, work.

A Markov chain is a probabilistic sequence of states—a topic that

would later come up in my own research at MIT—and mathematical

psychologists were pioneering their use in simulating how a

learning brain might function. Bjork had tasked his simplified brain

with remembering pairs of items, just like in McGeoch’s study

thirty-odd years prior. His model stipulated the existence of a short-

term and a permanent memory state, but there was a problem:

information in the former didn’t seem to want to pass into the

latter. “There was no transition to this sort of permanently learned

state,” he said, which “was kind of shocking at the time.” What was

more surprising, however, was Bjork’s solution: He let the short-

term memory units engage in random acts of forgetting. With that,

the model began obediently chugging along, the to-be-remembered

information sliding perfectly into long-term storage. The outcome

sent Bjork on a career-long journey—first, to the University of

Michigan, then to his eventual academic home at UCLA—to figure

out why forgetting was so important, and whether what appeared to

be true in classroom-sized computers could be said for classroom-

dwelling humans.

—

And so it was at the UCLA Faculty Club, under a potted palm, that

Robert and Elizabeth Bjork, Robert’s longtime collaborator and

spouse, graciously agreed to sit for an interview. The Faculty Club is

a single-level oasis of a building, situated on a bluff, overlooking a

surface street chockablock with overstimulated motorists. Although

the campus’s famous inverted fountain wasn’t running, Los Angeles

was experiencing a welcome reprieve from the long drought that

had plagued it for years, as well as a spate of wildfires that had

overcast the city with smoke the month prior and would return with

a vengeance a month later. It was as though someone had hit the

pause button on the unfolding environmental calamities, just long

enough for a conversation about how to better leverage our species’

brainpower.

Robert and Elizabeth sat down with cappuccinos.

If, in the years following Robert’s turn to forgetting, it was

obvious to psychologists that there was a difference between

memories’ storage and retrieval strengths, it wasn’t clear what

exactly to do with that information. Together, however, the Bjorks

would go on to put forward an intriguing theory that didn’t just tie

the two together, but would position forgetting as fundamental to

how the learning brain works.

“What was really different, I think, and new with us, was this

idea, not that you needed these two strengths,” said Elizabeth, “but

that they interacted with one another.”

They had had their suspicions about the importance of forgetting

virtually from the start. After all, William James had suggested back

in 1892 that “if we remembered everything, we should on most

occasions be as ill off as if we remembered nothing.” The Bjorks had

been inclined to agree: Without forgetting, Robert predicted in 1972,

we would “degenerate” to a “state of total confusion.”

In an attempt to dig deeper, Robert—Elizabeth would formally

join later—began to explore different ways to make new memories

irretrievable. In a stream of studies running the length of the 1970s,

he and his research partners used a variety of tricks to lead their

study subjects to the shores of forgetfulness. The first of these

involved interleaving to-be-remembered information with

distractions, in the tradition of McGeoch. Robert also tried

physically moving his subjects—one room for learning, another for

assessment—the idea being that cues from one’s senses contribute

to which memories you can retrieve at any given moment. And he

explored spacing out study sessions temporally, which led to

forgetting in the short term, as anyone who habitually crams for

exams could tell you, even if it’s beneficial for long-term retention.

All of these tricks provoked measurable forgetting relative to control

groups.

He even tried to induce forgetting by simply instructing his study

subjects not to remember certain items. After a group memorized a

long list of information, Robert told them to forget it: that list had

just been for practice, and the real to-be-remembered list was

upcoming. After they had memorized the second list, Robert tested

them on both anyway. Somehow, his instructions had gotten

through: compared to a control group, their recall of the first list

was impaired, and the second list enhanced.

Far more interesting than all the various ways Robert induced

forgetfulness in this multiyear series of studies, however, was what

happened afterward, when he gave his subjects cues to help them

remember what they’d lost. Thus refreshed, the memories didn’t

just return, but came roaring back as though they’d been given a

new lease on life and wanted to make the most of it. These

forgotten-then-rejuvenated memories appeared to be both more

readily accessible and stickier than memories that had never been

lost in the first place.

For a common example of the power of forgetting-then-

relearning, Robert suggested thinking of an all-too-common social

challenge: “You’re at some meeting or party or something where

you really want to try to remember the names of the people you’re

meeting,” he said. When confronted with a new name to remember,

“One thing people do when they’re really concerned is kind of repeat

it over and over to themselves. Not out loud, of course.” The tactic

helps, but only for a short time: “That won’t do anything as far as

creating long-term learning,” he said. And so later in the night, you

find yourself faced with competing possibilities: Was he James,

John, or Jake? Suddenly, an hour later, the name comes back: Jim,

of course. Having forgotten a name, says Robert, then, “at some

time later, looking across the room and retrieving what that

person’s name is—that can be a really powerful event in terms of

your ability to recall that name later that evening or the next day.”

Relying on just the power of forgetting and retrieval alone,

students and teachers alike can glean impressive ways to improve

their study habits and instructional tactics. According to Robert’s

early results, for instance, the long-lasting mnemonic benefits of

spaced-out study sessions could be explained not only by synaptic

strengthening at the cell level, but also at a level higher up the

cognitive high-rise, where spacing boosts retention by making

forgetting and re-remembering possible. “There have been

arguments off and on about the mechanisms” involved in spacing,

said Robert, “and sometimes we think that all the explanations may

be correct. They’re not mutually exclusive.” Mix in the confounding

effect of interleaving, as I’ve noted—alternating one spaced-out

study session with another—and you have the potential for deep,

robust memories, provided, of course, you eventually retrieve what

you forget during these exertions.

But the Bjorks were just getting started. Of particular interest

was Robert’s finding regarding directed forgetting, where he had

simply told his students not to remember something, and they had

miraculously complied. What mechanism, he wondered, could

possibly produce an effect like that?

—

During the 1970s and most of the 1980s, Elizabeth had to content

herself with a background role in this line of research.

“There used to be nepotism laws,” explained Robert.

“That was part of it,” she agreed.

“For many years those laws penalized women. If a couple went

somewhere, the man got the job,” he said. “When we came to the

universities here, I think we were once told we were the second or

third couple in the whole—”

“System,” she said.

“UC system,” said Robert. “But then there was this period where

there weren’t the nepotism laws anymore, but there were informal

things like, ‘you shouldn’t publish together,’ or ‘you needed to work

in different domains.’ So even though Elizabeth’s background was

learning/memory, she had an era of working on—”

“I turned myself into a visual cognition person for a while,” she

said.

“And did some things on children,” he said.

“And I also did some developmental stuff,” she said. “Although

we’d been working and talking the whole time.”

“The whole time, working and talking,” he agreed.

Including during the period leading up to a 1978 study Robert

coauthored, which was aimed at explaining the “mystifying ability

on the part of subjects,” as the authors put it, to forget items

seemingly on cue. The effort was only marginally successful, but the

finely tuned methods they employed happened to reveal something

unexpected. The act of retrieving items from memory didn’t just

boost their later retrievability, but also actively depressed recall of

competing items.

With the unexpected finding that the act of retrieval can modify

memory beyond the item being recalled, the Bjorks had their mise

en place: ingredients laid out, tools at hand. And, at long last, both

chefs dans la cuisine, ready to take on the master of learning, E. L.

Thorndike.

Slowly, universities began to come around on the idea that

married couples could work together, to the point where today,

hiring a couple at the same time has become a recruiting tactic for

many schools. And finally, after years of collaboration if not

coauthorship, the Bjorks produced a paper that, upon its release in

1992, resounded like a hymnal dropped in church.

It was “the first thing we published together,” Robert said,

“twenty-three years after we were married.” It was also perhaps the

single most significant update ever applied to Thorndike’s original

map of how learning works.

THE NEW THEORY OF DISUSE

If forgetting were purely a function of mnemonic decay, as

Thorndike posited in his theory of disuse, then it was purely

harmful: the sort of eternal enemy, like hunger or cold or death

itself, against which we animals have evolved to valiantly struggle.

Remembering everything we encounter, the thinking went, must be

expensive in terms of either bodily energy or data storage, and so at

some point, forgetting becomes inevitable.

In their 1992 publication, the Bjorks flipped that idea on its head.

What if, they mused, long-term memory capacity is, for all practical

purposes, limitless? After all, up and down the cognitive high-rise,

researchers had come to adopt a picture of memory that looked less

like a finite container to be filled and more like a growing tree, with

every new branch only adding to the total available storage capacity.

In such a model, might forgetting function less as an unavoidable

yin to memory’s yang, and more like a tool, evolved over the eons,

for pruning the overgrown Fragonard scene that is our tree of

knowledge?

Making such a tool possible was the interplay the Bjorks had

observed between retrieval strength and storage strength. Moments

after you first meet someone at a party, it’s very easy to repeat their

name to yourself, since retrieval strength is high. Meanwhile, in the

moment you register that name, its storage strength climbs from

zero to a low level. But repeating the name does little to increase

that storage strength. The reason why, according to the Bjorks, is

that there are diminishing returns to revisiting a memory while

retrieval strength is high.

“The higher it is in retrieval strength, when I produce it or study

it, the lower the increase in storage strength,” Robert explained.

Only once the memory’s retrieval strength drops as a result of

interference, whether due to the passage of time or encroaching

sources of confusion, do you get another crack at increasing storage

strength in a more significant way—such as at our hypothetical

party, when you dredged up the once-forgotten name after a time

lapse (Do you remember what it was?), and presumably attached

new associations to it as a result.

If you’re trying to remember something, said Robert, “storage

strength, just vaguely, would be how linked up is that thing with

related things in your memory. So, if it’s some event, or a friend or

teacher’s name from your past, maybe all the way back to high

school and stuff, it will be linked up with lots of things. Images of

the school, episodes you did together, semantic things.”

The sheer ballast of all those connections helps explain why it’s

almost always easier to relearn information a second or third time

around. It also affects retrieval strength. “That’s another thing in

our theory, that the rate at which you lose retrieval strength

depends on what the storage strength is,” said Robert. When storage

strength is very high, retrieval strength fades so slowly that it might

never go away—which is why a healthy person will always be able to

summon up the name of their mother, or George Washington. And

even when a memory’s retrieval strength does fade, the storage

strength remains, ready to rekindle that retrieval strength at a

moment’s notice. “As you move through your life and you change

contacts, and meet other people and so on, the name of the best

friend, or the best teacher you had, or whatever, won’t be recallable,

but it will be recognizable,” said Robert. “And if something—going

back to a class reunion or something—provides enough cues that

you start to recall and use it, there will be a huge increase in

retrieval strength that will become very available for quite a long

time.”

Put another way, if the experience of forgetting is actually the

loss of retrieval strength due to interference from other thoughts

and memories, then forgetting dials those interfering associations

down, close to zero. Retrieval reblazes the true path. The other

competing paths, meanwhile, fade relative to the correct path,

because the correct path is interfering with them.

But when storage strength is low—when that house in the woods

is more like a lean-to—retrieval strength fades fast. This is why you

can’t recall the name of the person at the party even minutes after

meeting him, no matter how many times you recite “Jim” to

yourself.

To pull an actionable takeaway from the Bjorks’ theory, then—

one that overlaps almost completely with findings from the synaptic

level of the cognitive high-rise—whenever a memory feels easy to

retrieve, doing so will not add much to its storage strength. But

effortful retrieval, made difficult by the strangling vines of

competing associations, adds to storage strength, and in turn

preserves retrieval strength for the long haul.

In terms of updating Thorndike’s map of the learning brain, this

notion of effortful retrieval soon took on great importance. By the

middle of the twentieth century, Thorndike’s model of decay had

received strong metaphorical support in the form of electronic

computer storage. Perhaps, many reasonably decided, we forget

things simply because we run out of space, like a hard drive filled

with photos. As the renowned ichthyologist David Starr Jordan once

complained upon becoming president of Stanford University, “Every

time I learned the name of a student, I forgot the name of a fish.”

In the Bjorks’ theory, however—which, in a direct shot at

Thorndike’s theory of disuse, they named the new theory of disuse

—there was no limit to the brain’s storage capacity. There were,

however, theoretical limits to the amount of information that could

conceivably be retrieved at any given moment.

“As we make some items in memory more and more accessible,

according to our theory of disuse, there is less and less remaining

retrieval capacity for other items. This viewpoint, then, may

exonerate the ichthyologist David Starr Jordan,” the Bjorks wrote in

their seminal paper outlining their theory. “He is often cited

uncharitably as someone who had a fallacious idea of the capacity of

human memory. Given the limit on retrieval capacity assumed in

our theory, however, an ichthyologist suddenly spending

considerable time learning and retrieving the names of a large

number of students could well lose access to the names of certain

fish.”

If retrieval strength were indeed a relative measure throughout

the brain, then it was also relative on a more local scale. Each

memory representation would have a variety of relatively strong and

relatively weak paths leading in. And each “cue”—a sensory or

cognitive impression that triggers a train of thought—would have a

variety of relatively strong and relatively weak paths leading out. In

the Bjorks’ model, then, effortful acts of retrieval (always in the

wake of forgetfulness) apply a Rototiller to your cognitive

landscape, prioritizing paths from cues to helpful memory

representations while weakening paths that might lead you to

confusion—cleaning away, in effect, superfluous and faulty

associations.

“Overall, it’s kind of adaptive the way it works,” said Robert.

Forgetting “frustrates people because obviously we’re all familiar

with not being able to recall things we want to recall. But on some

broad statistical basis, most of what we’re able to recall is things

associated with the current contextual cues—things that are more

relevant to current tasks and this phase of our lives.” Forgetting,

therefore, ensures access to the most important information for the

present, even as less immediately useful information is stored for a

rainy day—out of sight, perhaps, but never out of mind.

EFFORT GOES TO SCHOOL

As tidings of the new theory of disuse spread, educators looked for

ways to put the theory to work: to trace the latest updates from the

scientists’ maps onto the more practical charts currently in

classroom use. It soon became clear that the theory could be applied

almost anywhere learning was expected to occur.

Robert, for instance, began to direct a sliver of his attention

toward effortful retrieval in the context of motor-skill learning,

which gave him the opportunity to revisit one of his first loves: golf.

In a classic study from 1978, researchers had assessed the ability of

two groups of children to throw a beanbag into a target three feet

away; one group practiced only at that distance, while the second

group practiced from either two feet or four feet away, alternating.

At the end of the study, this second group outperformed the first

group at three feet away, despite never having practiced at this

distance. This result came as strong evidence of the power of

variation, but there had been no mechanistic explanation

forthcoming at the time. Now, well aware of the plausible

mechanism of effortful retrieval, Robert began noticing suboptimal

training patterns everywhere—particularly at the driving range,

where people typically train on one club ad nauseam, switching to a

new club only after a long period of massed practice.

“People do everything wrong on the driving range,” he said.

“They hit a good one, they rake a ball” over, and repeat, again and

again. “That’s just short-term motor-memory change. They don’t

interleave, they don’t space.” The approach can lead to noticeable

improvement within a given training session, but by the early

1990s, a growing list of studies was showing that such blocked

practice was suboptimal for the long-term retention of skills, as well

as transfer of skills among different tasks. One group of researchers,

for instance, had badminton players practice three different types of

serves in either massed or interleaved sequence. The former made

faster progress during the instruction period, but following a delay,

the latter group was not only more accurate, but also better able to

serve from the opposite side of the court—a position where neither

group had practiced.

One motor-learning idea from the mid-1980s that gained a new

mechanistic explanation in the Bjorks’ theory was the “reloading

hypothesis,” which holds that massing one’s golf practice is harmful

because it allows you to economize retrieval of the motor program

responsible for your swing. Golfers often “load” the program only

once, even if they hammer out ten or twenty repetitions in a row.

“They don’t ever reload the motor program,” Robert said. But

switching to a new club or picking out a new target with every

repetition requires you to reload the relevant motor program each

time. The effect is more effortful retrieval, and thus stickier and

more accessible skill memories. Robert, who has shot his age

ninety-six times since he turned seventy-two, has spread the gospel

of skill interleaving throughout the hallowed halls of golf, including

at the annual meeting of the PGA.

Back in the classroom, effortful retrieval has helped explain why

interleaving tends to produce better results than spacing alone. A

more recent technique, of which Elizabeth Bjork has become a

particularly outspoken proponent, takes effortful retrieval even

further. If retrieval can strip away faulty associations and rejuvenate

memories, why wait until exam time to retrieve the answers to

questions? Recently, Elizabeth has advocated for the practice of

pretesting, which is exactly what it sounds like: taking a practice test

prior to the real deal. Like so many threads relevant to the new

theory of disuse, research into pretesting can be traced back to the

1970s, when the first of many studies came back with results

showing that pretesting leads to marked improvement on final

exams. More recently, Elizabeth coauthored an intriguing article

showing that multiple-choice pretests can even improve retrievable

knowledge related to the incorrect answers. For instance, answering

a question about the oldest geyser in Yellowstone National Park

(Castle Geyser) also activates the potentially useful knowledge that

Old Faithful must be younger, and does so more effectively than

would passively reading that fact.

Despite how well the technique works, however, students often

meet pretests with protests. They take time, and more importantly,

the effortful retrieval they demand takes energy. This issue raised

one question that had been bothering the Bjorks since before they

published the new theory of disuse. Why, precisely, does effortful

retrieval have to feel so difficult? After all, there are plenty of

expensive activities—in terms of both calories burned and cognitive

resources utilized—that the brain rewards, ranging from curiosity to

sexual behavior. What was it about effective learning strategies that

made them seem so difficult?

DESIRABLE DIFFICULTIES

Answers to that question had already started to cross Robert Bjork’s

desk as early as the mid-eighties. In 1985, Robert had been asked to

join a committee of the National Research Council, underwritten in

great part by the United States military, tasked with investigating

any and all techniques that could conceivably produce better

soldiers, faster. The Committee on Techniques for the

Enhancement of Human Performance, as it was known, left no

learning-related psychological theory unexamined, no matter how

outré. Soon enough, to the dismay of science fiction fans

everywhere, it conclusively reported “no evidence of the existence or

usefulness of elements of parapsychology, including ESP, telepathy

or thought projection, and mind-over-matter psychokinesis,” as the

New York Times detailed in 1987. The committee was meant to be a

one-off effort, but new research questions popped up as quickly as it

could address them, and its work continued well into the mid-1990s,

when Robert assumed the role of committee chair.

During this time, amid such distractions as ESP and

parapsychology, a handful of promising, serious research threads

began to appear. Some of these, such as learning during sleep via

audio recordings, led nowhere. The idea of metacognition, however

—that is, how we think about our own thinking and learning—

proved so interesting, and fit so snugly with the new theory of

disuse, that it went on to influence not only the rest of the Bjorks’

respective careers, but, ultimately, maps of applied learning trusted

by educators in the field.

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In the history of learning research, the idea to study metacognition

came surprisingly late. Facts like the power of effortful retrieval

“have been known one way or another for a very long time, but it’s

almost like they can get forgotten sometimes in the domain of

education,” said Robert. “But the field of metacognition is much

younger. It took, I think, some of us quite a long time to see certain

relationships.”

In theory, the subject should have fit right into the wheelhouse

of researchers like Thorndike, who led psychology away from the

navel-gazing methods of “introspection,” as it was known, and

toward quantitative techniques that would yield hard data. Although

both Thorndike and Dewey variously flicked at it, metacognition

proved too slippery for quantitative analysis. There was no obvious

reason to doubt one’s own subjective sense of having learned

something or not, and so psychologists rarely bothered to ask how

those sorts of impressions could deviate from reality.

In the 1960s, however, that began to change. In the first modern

metacognition study, the psychologist Joseph Hart compared

people’s feeling-of-knowing, as he dubbed it, against known facts.

He worked from the assumption that we use some sort of static

metric, like an engine oil dipstick, to judge our own state of

knowledge about a topic. The follow-up research that caught Robert

Bjork’s eye, however, suggested a different automotive analogy: a

speedometer. In the same sense that a car’s speedometer infers

ground speed from engine rotation, we infer knowledge about the

state of our memory based on the speed and effort involved in

encoding and retrieval.

This speedometer can, however, be fooled, which is especially

distressing in the light of the many studies showing that students

tend to study a topic until they reach what feels like an acceptable

level of knowledge, but no further—a recipe for disaster if your

judgment of your own knowledge is off. And indeed, almost every

aspect of what we know about what we know, and our ability to gain

more of it, is fraught with potential inaccuracy.

For starters, psychologists have identified three major sources of

metacognitive bias regarding our ability to add to our own memory.

When information is laid out in front of us, hindsight bias causes

us to treat it as though we knew it all along—which becomes a

problem come exam time, when it turns out that what you thought

you knew is stored in your textbook, not your memory. Foresight

bias, meanwhile, is an artifact of how our memory is structured. A

given cue may reliably call up an answer, and we believe (at our own

peril) that we will be able to summon it again in the absence of that

cue. For instance, plenty of students might be able to answer a true-

or-false question concerning whether hemoglobin accepts oxygen in

the blood, but won’t be able to name the molecule when asked

point-blank. Finally, many of us demonstrate what Robert Bjork and

coauthors have dubbed a stability bias: the false sense that what’s

accessible or inaccessible in our memories will remain that way

over time. In fact, the information you can access shortly after

instruction is a poor guide to what you’ll be able to access at a later

date. Stability bias translates readily into both overconfidence (I

already know everything I need to know, so I don’t need to study)

and defeatism (I don’t get this topic and I never will, so why bother

studying).

In addition to the general distortion field cast by these common,

overarching biases, other factors can give us a wrong impression of

what we know, including how we’ve retrieved and encoded a given

set of facts. If you can call a fact to mind quickly and easily, for

instance, you might assume that it’s correct—but it might just be a

well-learned falsehood. Meanwhile, facts that feel easy to learn in

the moment don’t always remain easy to retrieve. That’s especially

true if they felt easy to learn due to the format in which they were

presented. Quite the contrary, in fact: In a remarkable series of

studies, learners described words that were delivered in larger type,

and at louder audio volume, as more memorable than quieter and

smaller words—an impression roundly disproved by subsequent

memory tests.

Robert Bjork, sensing a pattern nearly two decades before many

of the studies referenced above came out, realized that

metacognition was more than just a neglected facet of cognitive

psychology. In fact, it fit perfectly with his and Elizabeth’s new

theory of disuse. Perhaps, he reasoned, metacognition research

could combine, Voltron-like, with the new theory of disuse, and do

what neither could do alone: break into widespread educational

practice. On one side, you had learning techniques that were

untapped because there had been no room for them in Thorndike’s

original rules of learning; on the other, you had techniques that

were going unutilized because students mistakenly found them

ineffective, and thought that they made learning harder.

Upon the techniques that ticked both boxes, Robert bestowed

the name “desirable difficulties.” Spacing instead of massing

certainly made the list. It could neutralize the false sense of security

given by recently learned facts; plus, by giving retrieval strength

time to subside, it gave learners a chance to shore up storage

strength; plus, as an additional bonus, there were still all those

benefits at the synapse level that neuroscientists had been talking

about since the 1970s.

Interleaving created even more desirable difficulty: it

accomplished everything spacing did, only with more forgetting and

therefore better improvements to storage strength, as well as more

transfer between disciplines. Pretesting fit the bill as well: It

demanded effortful retrieval and came with the added benefit that

pretests didn’t lie about the state of one’s knowledge, unlike one’s

own feeling-of-knowing. In Robert’s book, even utilizing an

unexpected or slightly difficult-to-read font qualified as a desirable

difficulty.

In the mid-1990s, the Bjorks sent the idea of desirable

difficulties out into the world through the normal academic

channels, and then they waited. A handful of interested parties

latched on, but the bulk of teachers and students remained

oblivious. Then, in 2014, a pair of the Bjorks’ occasional research

collaborators, with the help of a professional writer, published an

excellent book filled with insights from cognitive scientists,

including the Bjorks, titled Make It Stick.

One reader of the new book was Louis Schulze, the new head of

academic support at Florida International University (FIU) School

of Law, a few blocks and a handful of bridge-linked islands from

Miami Beach. For years, the school’s bar-exam passage rate had

bounced around the middle tier of Florida law schools: number

seven out of the state’s eleven law schools in 2012, up to number

three by 2014, then down to nine as of February 2015. Schulze was

charged with turning around the school’s lackluster rates.

Traditionally, law schools looking to make big changes in bar-

exam passage without changing the composition of incoming

classes had sought to do so via what Schulze called “silver bullets”:

pouring resources into a class (usually civil procedures) or set of

classes that seem to wield an outsize effect. A data-oriented

colleague at FIU, Raul Ruiz, who arrived around the same time as

Schulze, ran the numbers, however, and showed that this approach

had never worked at FIU. It was time to try something new, and

Schulze decided to read the studies described in Make It Stick—

including the Bjorks’.

That year, he began a program, running in parallel to FIU’s

traditional law curriculum, designed to teach students how to

absorb the often-absurd amounts of information required of law

students. Today, the program unfolds over all six semesters. First,

Schulze offers a voluntary, zero-credit course, designed to teach

students such tactics as self-pretesting, as well as an optimized

approach to outlining course content (a common law-school study

method) that he has developed. “They have absolutely no

compulsion to be there whatsoever,” he said. However, in the

second, third, and fifth semesters, if you’re in the bottom 20 percent

of the class, continued instruction with Schulze on learning to learn

becomes mandatory. And finally, “the sixth semester course is the

big one,” he said. It’s optional, but “90 to 99 percent of the class

signs up for it now.” At this point, he said, “they’ve seen the success

numbers.”

Schulze’s program is designed not to add to the legal information

delivered in students’ other courses, but to complement it using

tools like desirable difficulties. “We’re not re-teaching law,” said

Schulze. “As matter of fact, we’ve got a ‘flipped classroom’ model

where they have to teach themselves the law outside of class, and

then when they come into class it’s the testing effect, it’s

metacognition, it’s spaced repetition.”

For some students, the program is a godsend. The rest of the

classes at FIU are still structured like normal courses, with high-

stakes finals that would, at least in theory, reward short-term study

techniques like cramming. But there’s a catch: In law school, there’s

too much material to fit into even a several-day cram session. “It’s

not like an undergrad course where you can maybe memorize ten

pages worth of material, walk in and then vomit that material on

your essay and be good to go,” Schulze said. “If you outline a

Constitutional Law class thoroughly, it’s going to be 120 pages.” To

convince his students to space out their study sessions, he pulls out

time-honored evidence: a version of Hermann Ebbinghaus’s

forgetting curve, applied to legal knowledge. “Basically, you take a

class on intent.” Two days later, your ability to retrieve that

information is “down to 30 percent. And then what law students do

is, they don’t touch that material again until ten days before the

exam. And so it flatlines throughout the entire semester at

30 percent, and then when they try to cram at the end, it only comes

back up to, like, 45 percent. And so I tell them if you use spaced

repetition, instead you’re going to walk into an exam with

80 percent of knowledge, but your colleagues are walking in with

45 percent knowledge.”

In 2015, just two years into Schulze’s program, FIU rocketed

from ninth place on the state’s bar passage list to first place. As of

2019, it’s maintained that position in seven out of nine of the state’s

semiannual exams administered thereafter, never dropping below

second place. The school’s “ultimate” pass rate—the percentage of

students who pass the bar exam within two years of graduation—is

now ranked within the top fifteen in the United States.

“We’re teaching them how to teach themselves better,” Schulze

said.

THE ANTI-WINNOWER

Perhaps the most inspiring aspect of FIU’s Academic Excellence

program, as it’s known, is what it does for students who might not

otherwise manage to fight their way into the legal profession. The

key, says Schulze, is the second- and third-semester courses,

mandatory for students in the bottom 20 percent of their class of

roughly 140 students. “A good chunk of those people, probably ten

of them, are failing out. They’re at a GPA below a 2.0. And if they

don’t get it up above a 2.0 by the end of the semester, they’re

academically dismissed,” he said. “So at that point I’ve got some

folks who are just like, ‘All right, I’m freaking out. I’ll do what

you’re telling me.’ ”

They don’t all adopt Schulze’s methods, and they don’t all

succeed.

But enough of them do. Enough to make a difference.

“That’s the group who, if you see why we’re now in first place,

that’s the group that really moved the needle for us, because they

went from a pass rate of something like low 60s, high 50s, to now

they pass it in the high 70s, low 80s,” he said. “I know anecdotal

evidence isn’t proof of anything, but one of our students last year,

who was, like, number three from the bottom of the cohort, he just

totally jumped into spaced repetition.” Over the course of his three-

year law school career, he went from complaining about what he

considered to be a sieve-like memory to raving about spacing.

Finally, as he walked into the bar exam, he’d been pretesting at

about 70 percent, a decent margin above the 63 percent needed to

pass. “So he was very comfortable going into the exam,” Schulze

said.

Results like these are always uplifting—especially when they

come to students as deserving as Schulze’s. “We’re very fortunate to

have students whose background is such that they work really hard.

We have a lot of first-generation Americans,” he explained. “We

don’t have that problem that some other schools have where the

students feel entitled to pass the bar exam. We don’t have that. Our

students scrap for it. And so I think that, while some of our students

may have come to law school from less privileged backgrounds,

they’ve got the intelligence, they’ve got the aptitude, they’ve got the

hard work,” he said. “When we just showed them, ‘here are the best

ways to teach themselves,’ it just unlocked their natural abilities.”

On the subject of FIU Law, said Robert Bjork, “Overall and

anecdotally, it has been remarkable when students have changed

their own routines to incorporate some of these desirable

difficulties.”

Perhaps what’s even more remarkable than the FIU results is the

simple fact that the Bjorks have shown that change is possible.

Disagreement about what constitutes improvements to education

may still linger everywhere in educational psychology, and even in

neuroscience. But at the very least, the Bjorks have shown that

updating the maps—both the scientific charts of the learning brain,

as well as practical maps for how to teach and learn—can have

immediate beneficial consequences.

The Bjorks’ research even carries critiques for the eternally

warring outside-in and inside-out camps. For those in the former,

who might assume “learning to learn” comes naturally in a project-

based curriculum, the Bjorks have strong words. Said Elizabeth: “So

much of our research has sort of shown emphatically that,” in

deciding how to best take in information, “if you just go with your

gut feelings, your instincts, what you think sounds good, what

should work—most of the time it’s incorrect.”

Meanwhile, the inside-out camp wades into equally dangerous

territory in its love affair with worked examples. There are no doubt

situations where “worked examples are better overall,” said Robert,

“simply because, perhaps, the learner in a given situation isn’t

succeeding enough,” and they need help getting over a problem-

solving hump. However, “I think just one key—and this goes across

sports and everything, I think—is just to get the learner to produce

something, one way or another.” Worked examples short-circuit

effortful retrieval, he explained, which remains the key to making

memories available in the long term. “There’s almost never going to

be anything quite as powerful as that. No way.”

As inspiring as the story of desirable difficulties may be,

however, it comes with a sobering dark side. Take Schulze’s success:

a wonderful story, except for the fact that it shows that in most mid-

tier law schools, students like his must be flunking out en masse—a

failure of education, a squandering of human potential, that we

should now recognize as entirely preventable. Robert Bjork and a

pair of coauthors made a similar point in a 2013 article on

metacognition. “There is, in our view, an overappreciation in our

society of the role played by innate differences among individuals in

determining what can be learned and how much can be learned, and

that overappreciation is coupled with an underappreciation of the

power of training, practice, and experience,” they write. This

combination “can lead individuals to assume that there are certain

limits on what they can learn.”

As I’ve noted, there is a multitude of reasons why the human

potential all around us goes unrecognized and unrealized. Many,

perhaps most, have to do with systemic injustices—societal failures

that it’s incumbent upon us to address directly. But these inequities

are often only compounded by the cognitive roadblocks we’ve set in

front of learners, and the cognitive blind spots that determine how

students are sorted.

I hope it’s now clear that we don’t have to live with these

stumbling blocks and blinders. There are steps we can take in the

here and now to clear them away. The same steps might not be the

right choice in every situation, and different approaches may appeal

to different practitioners. But the overarching point remains

undeniable: We can learn, and teach, differently. No longer

beholden to a nineteenth-century idea of the learning mind, we can

keep pace with science’s multiple, ever-advancing cutting edges.

In fact, not only can we put cognitive science discoveries into

practice, but I believe we’re ethically obligated to do so—posthaste.

As in the rare clinical pharmaceutical trial that goes so well that the

researchers pause the study and start handing out the lifesaving

drugs to the control group, the benefits of cognitively friendly

instruction are so profound that inaction at this point would be

tantamount to malpractice. We have knowledge that can save

students from the educational winnower and help them realize a

lifelong love of learning. It’s time to put that knowledge to work.

Part Two

MIND AND HAND

- VI -

VOYAGES

In our climb up through the layered disciplines of cognitive science,

we’ve only dealt in passing with how to apply their findings to

learning and teaching. Now it’s time to make the same turn that all

students of engineering must learn to make: to gather up our

abstract scientific knowledge and put it to work in the real world.

This transition is anything but straightforward. For one thing,

the real world places different demands on engineers than on

scientists. In the case of cognitively user-friendly learning, such

seemingly mundane details as whether a given pedagogical tactic

can be realized at scale, let alone cost-effectively, take on prime

importance. Even the most amazing instructional idea can never

live up to its transformative potential unless we find a way to open

the floodgates and let large numbers of people experience it—and

not just in their youth, but throughout their lives.

Meanwhile, the logical traps that bedevil basic science become, if

anything, more perilous in its application. When scientists

oversimplify, it’s usually by creating a model whose scope is too

small: failing to account for all the causes responsible for an

observed effect. Engineers, meanwhile—scientists inverted, in a

sense—tend to oversimplify by making scientific models too large:

stretching them to predict real-world effects beyond what their

logical skeleton can bear. Reductive thinking in science is never

good, but only in engineering does it become truly dangerous,

manifesting in bridges that collapse, financial instruments that

destabilize economies, drugs with unacceptable side effects,

winnowers that waste grain.

In any quest to apply findings from our cognitive high-rise, then,

the first step must be to understand what cognitive science research

doesn’t tell us. Perhaps most glaringly, when cognitive scientists

attempt to clarify how “the brain” or “the mind” works, they’re

generalizing: studying many individuals (even multiple species) in

an effort to paint a picture of a generic human brain, a generic

human mind. In reality, however, there is no single, typical human

brain. And so for any truly inclusive, cognitively friendly vision of

education to work in the real world, it will have to be flexible.

Wherever possible, it must tolerate individual variation in student

interest, motivation, prior knowledge, speed of learning in a given

subject, and far more.

Scalable, flexible learning that is optimized for cognition: any

one of these three engineering demands is challenging enough to

realize in a school. Taken all together, they raise a stark question:

Are the reforms we’re mulling even achievable within our inherited

educational institutions? Or will we need new institutions, built

from the ground up, to make these virtues possible?

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In fact, there’s quite a bit that an enterprising reformer can pull off,

even while confined by traditional educational structures. Part of

what makes the Florida International University College of Law

story so remarkable, for instance, is that it achieved its profound

reversal within the familiar trappings of law school education:

pontificating professors, semicircular lecture halls, final exams, and

so on.

MIT, too, has tested how much instructional change the larger

academic superstructure will tolerate. Fittingly, a literal space

explorer is responsible for the Institute’s initial giant steps down

this path. John Belcher was part of the team that built the plasma-

detection instruments on the Voyager 1 and Voyager 2 spacecrafts

and, during their flybys of Jupiter, Saturn, Uranus, and Neptune in

the 1980s, served as those instruments’ principal investigator.

Today, he spends much of his time poring over the data now

returning from the probes as they venture into interstellar space. In

between then and now, however, he turned his gaze to the

challenges of physics education—which, as lead lecturer for MIT’s

largest course, Physics II, he found he couldn’t ignore.

At a conference of physics educators in 1996, Belcher

encountered several different tactics for improving on the standard

lecture-and-recitation model. Like so many other frustrated physics

professors, he had observed that even top-tier students, even after

extensive physics coursework, still tended to come up with intuitive

but wrong answers to physics questions. The problem, he was told

by scholars who had studied their Piaget, had to do with the sorts of

explanations that students construct early in childhood for how the

physical world works. Upon encountering natural phenomena like

momentum, friction, and weight, children readily form personal

theories that are correct enough to serve their purposes in daily life,

but fail to hold up in the physics classroom. Correcting such

misconceptions required a deep remodeling of very old schemata,

densely interconnected with memories acquired over the course of

more than a decade. Such deeply held rules couldn’t merely be

reasoned away in the space of a lecture. No, they needed to be

eradicated roots to branches—an approach, he was surprised to

hear, few instructors had tried.

Already, however, that was beginning to change. Up the river at

Harvard, the physicist Eric Mazur had begun experimenting with

the first of two major innovations he would contribute to classroom

practice around the world. In his system of “Peer Instruction,” as he

named it, he encouraged students to explain confusing physics

concepts to each other. “You’re a student and you’ve only recently

learned this, so you still know where you got hung up,” he later

recalled. “Whereas Professor Mazur got hung up on this point when

he was seventeen, and he no longer remembers how difficult it was

back then.”

Peer learning acted sort of like a time travel device: allowing

professors to climb down one student’s schematic tree to meet

other students at their level. There was a problem, however:

Although the physical shape of traditional lecture halls exposed all

students to equal quantities of professorial wisdom, it prevented

them from easily speaking to one another.

Soon enough, however, Belcher discovered that a handful of

pioneering physics departments—most notably at the Rensselaer

Polytechnic Institute and North Carolina State University—had been

testing out a solution. “Studio Physics,” as it was known at RPI,

combined aspects of lectures, problem-solving recitations, and

laboratory work into a single block of time, and replaced the one-

way communicative architecture of the lecture hall with small

round tables and an open floor plan—perfect for instituting a

version of Mazur’s Peer Instruction.

Even better, the setup moved demonstrations down from the

lecture stage to the students’ tables, where they could physically

experience the objects and processes involved. To physics lecturers

of the old school, such touchy-feely accommodations might have

seemed unnecessary. But for a teacher hoping to undo physics

misconceptions formed in childhood, the approach made perfect

sense. According to the theoretical perspective underlying the

approach, known as embodied cognition, the brain is not

functionally limited to the neurons living in the skull. Rather, for all

practical purposes, it stretches out in neural networks running

throughout the body, which play crucial roles in early development

and, in adulthood, continue to factor into the encoding, retrieval,

and modification of memory. According to this framework,

experiencing a physics concept through one’s own hands would

create an overlapping yet distinct set of stored associations as

compared to reading about it, or observing it from a distance. By

encouraging such tactile experiences, studio physics could reinforce

students’ understanding of concepts—and, better yet, enable

professors to travel even further back through students’ learning

histories to address misconceptions where they were created, in

childhood.

Before Belcher and a group of like-minded educators could build

MIT’s own version of studio physics, however, there were still a

handful of architectural problems to overcome. For instance, in

studio physics–type classrooms, Belcher often observed a large

gaggle of students crowding around a single whiteboard, solving

problems. A bigger, better, tech-enabled classroom was needed—

which would be possible only with ample money and full buy-in

from the Institute. Belcher demanded and obtained both. As Peter

Dourmashkin, Belcher’s collaborator and eventual successor in this

effort, recalled: “He got the grants based on his reputation, based on

his experience at MIT. He was able to initiate the project, and he

built a team.”

At the time, there were a few major sources of grant money

floating around, in search of big promising ideas for education

reform. “A lot of other people got some money,” Dourmashkin said.

“But only TEAL”—as Belcher’s Technology Enabled Active Learning

system became known—“made it into the classroom.”

TEAL AND BEYOND

In space, there is no up or down. In a TEAL classroom, there is no

back or front.

As a result, if you were to sneak into a TEAL class at MIT, you’d

likely behold an apparently random system that, upon closer

inspection, betrays hidden organization, like the movement of

heavenly bodies. The professor—these days frequently

Dourmashkin—stands in the middle of the three-thousand-square-

foot space, surrounded by thirteen tables, at which sit nine students

apiece, divided into groups of three. Among those tables pirouette a

technical instructor, a grad student, and six undergraduate teaching

assistants, while on their Formica surfaces unfolds the music of the

spheres: classical, Newtonian physics demonstrations. (Or, in

Physics II, electromagnetic demonstrations involving, for instance,

tabletop Faraday cages.) Lining the walls, you’ll find whiteboards

and projector screens. Ceiling-mounted video projectors allow the

professor to multiply any group’s whiteboard thirteen times over, so

that the entire class can see it. At other times, he or she may project

advanced visualizations of complex electromagnetic fields,

generated using student data. (Belcher, who had developed an

abiding interest in electromagnetic field shapes dating back to his

early Voyager experiences, built the underlying software himself.)

Finishing the picture, anachronistically, are the desktop computers

on each table: holdovers from the classroom’s founding, a few years

before most students brought laptops to class.

Back in those days, when MIT made the sudden switch from the

lecture-and-recitation model to TEAL, the upheaval—both

architectural and cultural—was fresh, and skepticism emanated

from all quarters. “What we learned right from the start was there

were really three communities that you have to deal with

extensively,” said Dourmashkin: “administrative, faculty, and

student cultures. And if you neglect any of those, you run into huge

problems.” Students, for instance, chafed at being forced to attend

TEAL’s mandatory class sessions. (MIT students, perhaps more

than most, have a reputation for skipping lectures that cover the

same ground as a course’s textbook.) They also feared the group

work involved. To Belcher as well as Dourmashkin, a staunch Peer

Instruction believer who had collaborated with Eric Mazur, the

group-interaction aspect of TEAL was non-negotiable. It was

necessary not only to realize the benefits of peer-to-peer teaching,

but also for students’ development as future members of

laboratories and collaborative workplaces. The promise of collective

work, however, seemed to set off a Pavlovian trigger in students.

“Their idea of group learning was from high school,” Dourmashkin

said, where, as high achievers, many had grown accustomed to

getting stuck with the bulk of the work.

If students proved restless when TEAL began in earnest, some

faculty members found their cortisol levels spiking to equivalent

heights. “There were some faculty members who were upset that

they weren’t going to be lecturing anymore, and they did a lot of

kind of getting the students to petition against TEAL,” said

Dourmashkin.

“We feel that the quality of our education has been compromised

for the sake of ‘trying something different,’ ” read the 2003 petition.

“It should not be forced upon the majority of the student body.” In

its coverage of the issue, the student newspaper included critical

quotes from prominent professors. TEAL had “a whole spectrum of

problems,” said one physicist. “Many students are really angry.”

And so, for a moment, TEAL seemed in real danger. Had TEAL

changed too much about traditional physics education, too quickly,

and with too little respect for the institutional norms and bylaws

surrounding it?

Ultimately, with an outspoken set of students and faculty in

revolt, it was a group of administrators who saved the day. The

larger physics department understood that the program would

experience atmospheric turbulence on its way to stable orbit, and

came through with the one resource that mattered above all others:

patience.

A few years were exactly what the TEAL team needed. Training

teachers, which had taken a back seat during the program’s initial

launch, took on primary importance. Some were so accustomed to

delivering traditional lectures, Dourmashkin said, that “they wanted

to take out space in the classroom and make a tilted floor.”

Retraining them “was number one,” he said. “Two, we had taken

data.” Within a few years, they could “show that the students in

TEAL had higher learning gains than students who were in the

lecture.”

From the start, TEAL had been set up not just as a classroom

intervention, but also, in the tradition of Dewey’s Laboratory

School, as an experimental one. By 2006, the results from the

experimental effort, led by Yehudit Judy Dori, an education

researcher at the Technion, in Haifa, Israel, were rolling in. The

experiment relied on a variety of assessment techniques, but

perhaps most important was a testing regime, posed to students

before the course and after, featuring the sorts of conceptual

questions that tend to expose inert knowledge.

By the end of the semester, TEAL students answered those tricky

conceptual conceptions twice as well as those who went through the

old lecture format. The TEAL failure rate, meanwhile, was less than

half that of the lecture. Eighteen months later, TEAL students still

outperformed the traditional class.

TEAL’s greatest beneficiaries were women. To the shame of

introductory physics courses around the world, men have

historically outperformed women—an indication of structural bias,

not aptitude, that contributes to continued gender imbalance in

professional physics research and engineering. “I think physics was

an older kind of gatekeeper style of learning,” Dourmashkin said.

“This was driving a lot of women out of physics, and I think the peer

collaborative environment changed that.” The findings tracked

closely with similar research from a Swarthmore-based team that

included Mazur, which had shown that Peer Instruction in various

contexts boosted both men’s and women’s academic performance,

but women benefited more. In the specific case of TEAL, in some

semesters women accounted for all six of the laboratory’s

undergraduate teaching assistants. That set a tone: Whenever a new

group of students walked into such a classroom for the first time,

“the first thing they saw,” said Dourmashkin, were the female

students who would help lead the show that semester. “I think that

delivered a really interesting message to everybody.” Today, in

TEAL-based physics classes at MIT, the gender performance gap is

gone. “If you look at final exam scores,” he said, “the average is

almost identical.”

SPACETIME

Since its invention in 2001, TEAL has spread around the world, and

up and down the age spectrum. The results keep rolling in. In

Taiwan, for instance, the introduction of TEAL didn’t just boost high

school students’ exam scores, but it also added to their self-reported

interest in physics in general, and participation in extracurricular

science programs. At the University of Kentucky, the introduction of

a fifty-four-seat TEAL classroom reversed the gender gap and then

some: women went from underperforming men by 5 percent to

outperforming them by 10 percent. Without the right instructor, the

classroom itself isn’t a wholesale guarantee of success, as a study of

college-age students in Taiwan showed—which echoed MIT’s early

experience with untrained TEAL instructors. The same study did,

however, reaffirm the findings from other countries: In the new

TEAL classrooms, women thrived.

Looking back, TEAL’s early success in keeping women from

being informally winnowed out of careers in physics and

engineering is one of the most inspiring results the team could

possibly have asked for. The fact that TEAL has since spread, thanks

in great part to MIT’s bully pulpit, and is ushering more women into

the fold, only confirms its status in my mind as an unmitigated

success story.

But perhaps the most intriguing part of that story is that TEAL

accomplished so much in those early years with one hand,

technologically speaking, tied behind its back. Initially, the

“Technology” component of Technology Enabled Active Learning

referred to matters having to do mainly with space: video cameras

projecting a single group’s whiteboard around the room; complex

field simulations tied to desktop experiments.

Far more revolutionary, however, was TEAL’s follow-up

technological wave, which pushed the boundaries of time.

For one example, take Eric Mazur’s second major contribution to

classrooms, for which he has become justly famous: the Personal

Response System, or “clicker.” The technology will be familiar to

anyone who has ever seen the game show Who Wants to Be a

Millionaire: a handheld radio device that allows a large studio

audience—or classroom—to answer multiple-choice questions en

masse.

Clickers, which have long since become a common sight in large

university lecture halls, allow professors to gauge student

comprehension of a given topic before moving on to the next. In

retrospect, the idea seems almost obvious. After all, teachers have

always relied on informal polling techniques to determine when to

move on: We pose questions; we look to see how many heads are

nodding. All clickers do, in theory, is beef up such methods’

statistical accuracy.

But the technological premise of clickers is more profound than

that. It hints at a possible change to the status quo that is not

incremental, but qualitative. In its small way, in fact, the clicker

represents an act of rebellion against a rule of school predating even

Thorndike: that students should keep up with their teacher. With

clickers in hand, students help set the pace.

It is joined in its revolt by another technique used in many

forward-looking classrooms, TEAL included: “blended” or “flipped”

learning. In such approaches (the former tends to be a measured

version of the latter) students take in some or all lecture content in

video form prior to class, and then complete some or all of their

homework during classroom hours, with instructors close at hand

and ready to help. As far as classroom trends go, nothing is quite so

trendy as “flipping.” In one 2016 survey, 55 percent of college and

university instructors said they were in the process of flipping or

blending at least one of their courses. In the case of MIT’s TEAL

classes, Dourmashkin and the other instructors make the requisite

video lectures themselves, not in an auditorium but a black-box

studio, separated from the camera by a well-lit pane of glass. Onto

this surface, they write and draw diagrams in Day-Glo marker as

they lecture, which, because the video can be mirror-reversed after

the fact, allows them to face their students while writing—a

professorial first.

Taken together, both clickers and flipping classrooms represent

some of the biggest changes to classroom practice since chalk met

board, and the reason why they feel so profound is devastatingly

simple. They challenge the most fundamental assumption of

contemporary mass education: that learning must be parceled out

not in units of knowledge, but units of time.

From early youth up through high school, college, and even into

graduate school, our progress as learners is measured in the

number of hours we spend in chairs in classrooms, the number of

weeks those classes take to run their course, and the number of

years it takes to earn a degree. Courses trundle along at the same

pace for students pulling A’s and C-minuses alike—frequently to the

boredom of the former and terror of the latter.

Clickers and flipped learning practices occupy a unique position

in modern education because they break the spell of time-centric

education without violating school’s many other inherited

institutional structures. With a clicker on your desk, you can vote to

slow down or fast-forward your professor’s delivery; watching a

video lecture at home, you can do the fast-forwarding and rewinding

yourself. However, your course still fits into a larger, time-centric

arc: at the end of the semester, you will still receive a grade

representing knowledge accrued as a function of time. That grade,

meanwhile, will still fit into your transcript, just as the course fit

into your semester’s schedule, just as your classroom—even a new,

high-tech TEAL classroom—fits into the physical architecture of

your school.

All told, a given course may play fast and loose with space and

time, but, like an episode of Monty Python airing between news

programs, it’s just a modular bit of wildness shoehorned into an

otherwise staid structure.

Engineers have an expression for the expected performance

limits of a given air- or spacecraft: the flight envelope. To exceed

those limits is to push the envelope—an expression that has long

since escaped into the vernacular. The MIT TEAL program pushed

the envelope of the traditional classroom model so far beyond its

design specifications that it nearly crashed after liftoff. (Instead, all

it broke was records.) But now, it’s not clear how much more

modification it can handle.

The TEAL diaspora is now part of MIT’s worldwide legacy. But at

the same time, one can’t help but wonder what we could accomplish

without the program’s inherent limitations: time-centrism, the

encroaching administrative superstructure, and—not to be

overlooked—TEAL’s cost, which can be prohibitive for even well-

heeled schools.

One need not wonder too long, however. In fact, in the early

1800s, the world very nearly embarked on a very different system of

mass education—an exceedingly economical one, as it turns out—in

which knowledge, not time, reigned, and which had its own unique

rules of school to reflect that fact.

As I’ll discuss in the chapters ahead, learners are only now

starting to find their way back to similar approaches via a variety of

independent paths, aided in many cases by technologies of the sort

used in TEAL classrooms. The vast majority have no idea that

societies around the world have seen this idea before—that they

tried it and, despite its theoretically impressive pedagogical power,

discarded it. Now, as we find our way to similar strategies, it’s

essential to understand what happened, and why. We must travel

back to see the world as the young Scotsman Andrew Bell saw it—

before he changed the very history of education, and before

educational history forgot him in return.

THE MALE ORPHAN ASYLUM

In June 1787, when Bell stepped off his ship into the Indian port

city then known as Madras, he merely intended to stretch his legs

for a day or two before re-embarking for Calcutta. He ended up

walking into a crisis—and staying a decade.

In the 1780s, India was suffering the spread of colonial rule,

mainly under the British, and that stranglehold was only growing in

strength. Earlier in the century, France had been the dominant

colonial power on the subcontinent, but in India, like just about

everywhere else, the French came to blows with the British, and by

1783, the latter had emerged as the clear favorite.

Looking back on this period, one aspect of the occupation that

doesn’t get nearly enough attention was the large number of Indian

women who became pregnant with the children of colonial soldiers,

whether due to rape or coercion or merely the prospect of a

marginally better life under oppressive rule. Many of those soldiers

then died or were called away to serve elsewhere, leaving these

women and their children behind. Despite the fact that most of

these children had living mothers, the colonial government

considered them to be military orphans, and determined—often, it

must be said, against the will of the mothers—that something had to

be done about their housing, feeding, and education.

This challenge would become Bell’s primary concern during his

time in Madras, the city later (and more correctly) known as

Chennai. As he stepped off the ship at age twenty-eight, he was

crackling with unrealized potential. He’d traveled abroad once

already to seek his fortune: to the American colonies, which had

declared independence while he was there. He barely lived to tell

about it. Right before the Revolutionary War found its way to

Virginia, where he’d been living and working as a tutor, he fled on a

Britain-bound ship. On his way to the docks, he even passed the

Marquis de Lafayette—the French general who came to the aid of

the Americans—headed in the opposite direction. Bell’s ship struck

ground off the desolate shore of Nova Scotia, however, and for

several weeks, the ship’s crew and passengers camped on a

snowbound island, freezing in the Canadian spring. Finally, after

being rescued by a whaling ship and recovering in Halifax, Bell

returned to his native St. Andrews, where he nearly died twice: once

due to a sore throat so severe he couldn’t swallow for three days,

and once in a pistol duel, which happily resulted in no injuries.

Fate, having evidently realized that killing Bell wasn’t worth the

effort, decided instead to take his side. Bell’s father had found

himself the swing vote in the election that would determine the

town’s representative in Parliament, and the resulting winner

promised to take an interest in the young Bell. This initially took the

form of advice not to go into the Church of England, which Bell,

who was ordained a priest in 1785, ignored. Two years later, more

fruitfully, Bell’s patron came through with an honorary MD from

St. Andrews University, a berth on a ship bound for Calcutta, and

letters of introduction.

These letters were of no use in Madras, but by the time the ship

arrived there, Bell had ingratiated himself with the captain and

other dignitaries onboard by giving lectures and aiding in

naturalistic observations. Armed with a whole new slew of

introductions, the young Reverend Doctor made something of a

splash in Madras society. He began delivering paid lectures that

soon amounted to major social events. Bell demonstrated for his

adoring onlookers the principles of electricity, created India’s first-

ever artificial ice, and built the subcontinent’s first hot-air balloon.

As his earliest biographer recounted: “It was of no great

dimensions; for as the assistant did his part badly, and the thing

failed, Dr. Bell (in his own words) threw it in a passion from the

verandah. After which the heat of the sun rarefied the enclosed air,

and the balloon mounted in grand style.”

Bell’s growing legend in Madras caught the attention of the

backers of the Male Orphan Asylum, who were in the market for a

suitable superintendent. He readily accepted the job. The asylum

would take several more years to get off the ground, however,

during which time Bell continued to lecture for cash. Even more

financially rewarding were his chaplaincies. Upon arrival in Madras,

he quickly became a chaplain of a local regiment, then another,

until he held a total of eight chaplaincies at the same time, which

added up to generous pay for relatively little work.

In 1789, the East India Company opened the Male Orphan

Asylum in an enormous structure known as the Egmore Redoubt,

which had been used to house gunpowder and had, in its relatively

young history, already been blown up twice. (One of Chennai’s train

terminals now stands at the site.)

From the start, the asylum was a necessarily lean organization.

Its main funding sources were an allowance provided by the East

India Company, charitable donations, and fines imposed upon

British soldiers for drunkenness. These (especially, one assumes,

the last) added up, but weren’t equal to the challenge of housing

and educating the local “orphan” population of 230 boys. When Bell

first joined, the school was teaching, feeding, and sheltering just 20

of them, although this number soon increased to 100 as funding

sources began to congeal. Against the advice of his friends, Bell, who

was not yet wealthy, volunteered his services gratis, surviving on

the combined income of his chaplaincies and lectures.

Initially, Bell’s attention was so preoccupied with such concerns

as feeding, clothing, and inoculating his students against smallpox

that he had little time to think about their education. The school’s

original uniform and bedding proved insufficiently warm in the

rainy season, and its board insufficiently nutritious. Cold and

hungry, most students became infected with roundworms, and

many with measles. At one point, nearly a third of the student body

could be found in the local hospital, and a medical report

characterized many of the children as “so puny, that it must be great

care indeed which could save them.” During the school’s first three

years, Bell lost four students to disease, including smallpox. It could

have been worse: The measles “proved less fatal than had been

apprehended,” one biographer reported.

Educating the children added a whole separate order of

difficulty. When he took control of the asylum, Bell assumed

authority over two assistant teachers, known as “ushers,” and one

headmaster. From the start, Bell was astounded by their inability to

teach, especially when it came to the youngest students and the

alphabet. But every time he managed to hire a suitable new

assistant teacher, a better position for that person seemed to open

up elsewhere. And in the meantime, it seemed that whenever he

suggested changing this approach or that, his remaining assistants

took umbrage and dragged their feet.

It was with all these frustrations whirling that Bell took a

morning horseback ride along the Madras coast. He happened to

pass an open-air Indian school, where he observed something

curious—to his eyes, anyway—taking place. Tracing figures in sand

on the beach, older children appeared to be teaching younger

children to write. He stared, and then took off—at a cinematic, sand-

spraying gallop, I like to imagine—crying “Eureka! I have discovered

it!” as he went.

He wasn’t the first, nor would he be the last, colonizer to claim

to have “discovered” something that a society had been doing for a

long time. What he’d stumbled across was likely a common

vernacular school, where education was conducted in one of the

local languages—likely Tamil, Telagu, or Marathi—as distinguished

from more rarefied schools, often conducted in Sanskrit. In South

India in the eighteenth and nineteenth centuries, a common

instructional technique at such vernacular schools involved one

student writing figures from, say, a table of weights and measures,

reading them aloud, and a group of his fellows following his lead

and rhythmically reciting it. It was probably this tactic or something

very similar, and the fact that the boys were enacting it by tracing

figures in the sand, that made Bell do his best Archimedes

impression and cry “Eureka” all the way home.

THE SCHOLAR FINDS HIS LEVEL

Back at the Male Orphan Asylum, Bell instituted changes. He

started by providing each of his youngest students with a small tray

of wet sand. He told his adult teaching assistants to instruct them to

write their letters in the sand using their fingers, which created a

reusable writing surface that would never run out of space, unlike

the expensive copybooks then in use. “It engages and amuses the

mind,” Bell later wrote, “and so commands the attention, that it

greatly facilitates the toil both of the master and scholar.”

Despite these benefits, Bell’s assistant in charge of the youngest

children told him that such a departure from tried and true methods

would be impossible. Frustrated, Bell decided to borrow the other

surprising practice he’d observed at the beachside school: mutual

instruction. He began paying one of his older students, one John

Frisken, a small fee to teach the youngest children their letters

using their sand trays. In this very early vindication of Peer

Instruction (at least according to Bell’s sometimes hagiographic

early biographers), Frisken soon easily outdid the adult teaching

assistant, and Bell expanded the practice of paying older students

small sums to teach younger ones. What worked in one class proved

successful in others, and Bell soon had regiments of boys working

under each other’s tutelage.

“The school is arranged in six or eight classes,” Bell later wrote,

in a pamphlet he would use to spread the word about his system to

the Anglophone world. Bell’s students were not grouped into classes

in the sense that we now understand them, where every student is

fed information at the same rate. “No Class is ever retarded in its

progress by idle or dull boys,” he wrote. Rather, classes remained

static while learners moved through them at their own pace, like

martial artists earning new belts, or skiers advancing from blue

squares to black diamonds. In Bell’s system, a boy at the top of his

class was given the opportunity to jump up to a higher class, where

he would start at the bottom. He would be given a few days to climb

up to the middle, and if he failed to do so, he would be demoted to

his earlier class, where he would remain until ready to try to climb

again. Meanwhile, any boy who repeatedly failed in his daily lessons

would slide back one class, where he would sit at the head of the

group. If his performance continued to slip, “he is doomed to

permanent degradation,” Bell wrote. “But, if he maintain a high

rank, he is allowed to resume his original Class on a new trial; when

it often happens that, by redoubled exertion, he can now keep pace

with them.”

Within each class, Bell arranged his students into pairs of pupils

and tutors, the latter of which received additional instruction

outside of school hours. “Mark, at the outset, how many advantages

grow out of this simple arrangement,” he wrote. “First, the very

moment you have nominated a boy a Tutor, you have exalted him in

his own eyes, and given him a character to support, the effect of

which is well known. Next, the Tutors enable their Pupils to keep up

with their Classes, which otherwise some of them would fall

behind.”

This last point, to Bell, was of the utmost importance. To this

day, falling behind in class remains a self-compounding problem,

with one unlearned fact leading to another, then another. “This,” he

wrote, “is the reason why some boys in most schools are declared

incapable of learning.” The blame didn’t rest with them, he argued,

but with their instructors. “It is you,” he wrote, addressing their

hypothetical teachers, “who do not know how to teach, how to arrest

and fix the attention of your pupil: it is not that he cannot learn, but

that he does not give the degree of attention requisite for his share

of capacity.”

There were other advantages to Bell’s system. Teaching a

concept seemed to help the tutors learn the material more

effectively than if they had taken it in only passively, an experience

Bell remembered from his younger days as a tutor and which, years

later, Robert and Elizabeth Bjork would recognize as an example of

retrieval practice. The system also relied on quick, fifteen-minute

lessons and hands-on work (including a requirement that every

child who graduated from wet sand trays to paper first had to

construct his own pen).

To keep the boys on task, Bell instituted a complicated system of

rewards, which he believed motivated students more effectively

than the fear of punishment. He reserved classroom discipline

solely for unruly behavior, not academic underperformance, and

limited punishment to such measures as detention and writing

assignments, which were doled out by a jury of the accused’s peers.

Corporal punishment, youthful memories of which haunted Bell,

was verboten.

As the full scope of Bell’s changes came into view, his

headmaster and assistants rebelled. By the time the headmaster

handed in his resignation, Frisken was eleven years old and running

a third of the school. Bell did manage to retain some of his assistant

teachers, however, who became engaged less with teaching than

with the task of ensuring that the boys didn’t abuse their newfound

responsibility over one another. “Such interference prevented all

that tyranny and ill usage from which so much of the evil connected

with boarding-schools arises,” wrote one of Bell’s biographers.

That probably wasn’t entirely true; bullies tend to find a way. But

still, by Bell’s account, anyway, the system appears to have worked

on levels both academic and—crucially, for our purposes—financial.

Expenses, on a per-student basis, fell substantially following the

institution of Bell’s new system. Initially, the school’s overall per-

student expenses amounted to roughly ten rupees per month—and

that was before Bell demanded improvements in the students’ diet

and dress. His new system, however, together with other

efficiencies he’d discovered along the way, such as owning milk

cows instead of paying for milk, meant that the asylum could now

house and educate each student for a little more than six rupees—a

cost reduction achieved apparently without any compromise in

terms of dress, room, or board. “On no occasion, and on no account,

had ever any deduction been made from the allowances of the

boys,” Bell claimed.

In the asylum’s full-blown form, its student body of two hundred

was taught almost entirely one student to another, with none of the

students older than fourteen. By 1792, Bell was crowing about his

new system in letters to friends in Britain: “Every boy is either a

master or a scholar, and generally both. He teaches one boy, while

another teaches him. The success has been rapid.” Mothers, Bell

wrote, had initially mourned the loss of their sons to the boarding

school—and for good reason, since many were coerced into sending

them. But under his new system, he claimed, they “ply us now with

every species of importunity to have their younger children

admitted.” Living British officers, meanwhile, fought to have their

sons educated alongside the asylum’s orphans. “We have already

more than thirty boys, white and blue”—the term for a child of

mixed parentage—“of this description, though they are subjected to

the very same treatment, dress, discipline, and diet, as the poor

orphans,” wrote Bell. “This I consider as the best commendation of

the Asylum.”

—

Bell set sail for Britain in 1796 because he’d been told the climate

there would benefit his flagging health. Returning with £25,000 and

an East India Company pension to his name, he proceeded to go

through the motions of settling down. He bought a sizable, rent-

bearing Scottish estate; accepted a rectorship in Dorset (where he

successfully vaccinated his congregation against smallpox); and, “at

the not immature age of 47,” noted one biographer, he married one

Agnes Barclay, the daughter of a local minister. With his roots once

again established in British soil, he spread his branches. In 1797, he

had printed one thousand copies of a book describing his

achievements in Madras, and handed them out to every influential

person he knew.

“You may mark me for an enthusiast,” Bell wrote in a letter to

the book’s printer, “but if you and I live a thousand years, we shall

see this system of education spread around the world.”

By the next year, England’s first Madras-style school appeared. A

few sprung up, or were converted to the Madras system, annually

for several years after that. Enthusiasm for the system soon began

to multiply thanks in no small part to endorsements from such

quarters as the archbishop of Canterbury, a number of influential

lords, and even the poets William Wordsworth, Samuel Taylor

Coleridge, and Robert Southey—the last of whom wrote Bell’s first

major biographical treatment, published in 1811. That same year,

the National Society for the Education of the Poor in the Principles

of the Christian Church, a powerful group with a self-explanatory

title, was founded and set up all of its schools according to Bell’s

system. By the time of Bell’s death in 1832, this organization was

running the Madras system in more than twelve thousand schools

in Great Britain and its colonies. And that was just the one

organization: Madras also found its way into other systems of

charity schools and was exported far abroad, from the Caribbean to

Oceania and South Africa, even to Russia. It could even be found in

snowy Nova Scotia, where Bell had been shipwrecked decades

earlier.

Although Bell’s system overtook most of the English-speaking

world and then some, there were exceptions—including, critically,

the young United States of America. The problem wasn’t that

Americans were opposed to the system. Rather, it was that the

United States was the stronghold of Bell’s greatest rival, who had

started out as his biggest supporter.

—

Bell and his wife first met Joseph Lancaster in 1804 at their home

in Dorset, where they greeted the young man warmly. Lancaster,

twenty-five years Bell’s junior, was developing an educational

scheme that would ultimately share a number of features with

Bell’s, including a large, one-room schoolhouse, instruction that

passed from one pupil to the next, and the use of trays filled with

wet sand. Bell and Lancaster tolerated each other in those early

years, but a schism soon formed: Bell was loyal to the Church of

England while Lancaster, a Quaker, insisted that his schools’

Christian instruction remain nondenominational. As a result, Bell’s

version of “monitorial” education, as the systems became known,

retained the advantage wherever England held sway, while

Lancaster found success elsewhere, including Gran Colombia (now

Venezuela), Mexico, and the United States. Lancaster’s custom was

especially welcome in the Quaker city of Philadelphia and nearby

New York City. There, he found a champion in DeWitt Clinton, the

most powerful politician in the state.

In the young United States, there was a particular urgency

animating the drive for mass education. The American republic was

still new, and its system of government untested. Today, a

representative government may seem like a fairly stable way to run

a country, but at the time, there hovered the ambient worry that the

forces of anarchy and monarchy would prevail. The most obvious

way to keep them at bay was through education. As Thomas

Jefferson argued in 1778, at the height of the Revolution, “those

entrusted with power have, in time, and by slow operations,

perverted it into tyranny,” and that “it is believed that the most

effectual means of preventing this would be, to illuminate, as far as

practicable, the minds of the people at large.”

It was in this spirit that Philadelphia and New York began to look

into establishing modest systems of public schools for their poorest

kids. This push predated modern tax-funded education, which

meant that the charitable organizations behind the schools were

constantly scrambling for money. As a result, when Lancaster

appeared, promising maximal education per dollar spent, they rolled

out the red carpet. In a speech given at the opening of a

Lancasterian school in New York City in 1809, DeWitt Clinton

waxed rhapsodic: “When I perceive one great assembly of a

thousand children, under the eye of a single teacher, marching, with

unexampled rapidity and with perfect discipline, to the goal of

knowledge, I confess that I recognize in Lancaster the benefactor of

the human race.”

Although the early 1820s were a heady moment for

Lancasterism, even then gears could be spotted flying out of the

supposedly flawless machine. True, whenever DeWitt Clinton

visited one of Lancaster’s schools, he beheld scenes of perfect

concord, but then again, he was one of the most eminent Americans

alive. As one Albany schoolmaster put it in an 1818 letter to him,

“There is as much waywardness in the youth of Lancasterian

schools as of any other. Oft does the proud spirit of Fredonia’s sons

rise in mutiny against the authority of one whom they consider at

least no better than themselves;—but I presume you never saw that

system in operation, but when DeWitt Clinton was present. When

such a name was but whispered round the School, what stillness!

what subordination! what assiduity!”

Indeed, discipline was enough of a concern in Lancaster’s

schools that their founder experimented with a baroque system of

almost gleefully creative punishments to keep his students in line.

Though technically considered non-corporal at the time, these

would send parents today in search of a police officer, lawyer, and

therapist, in that order. A child who broke the rules one too many

times could wind up with a “wooden log round his neck,” Lancaster

explained in an 1803 treatise. “While it rests on his shoulders, the

equilibrium is preserved; but, on the least motion one way or the

other, it is lost, and the logs operate as a dead weight upon the neck.

Thus, he is confined to sit in his proper position.” That wasn’t all. A

student who broke the rules could also have his legs attached

together with wooden shackles: “Thus accoutered, he is ordered to

walk round the school-room, till tired out.” If that didn’t work,

Lancaster suggested tying the student’s left hand behind his back, or

his elbows together. When offenders erred in pairs or groups, they

could be “yoked together sometimes, by a piece of wood that fastens

round all their necks: and, thus confined, they parade the school,

walking backwards.” For repeat scofflaws, Lancaster reserved his

most bizarre and degrading punishment. “Occasionally boys are put

in a sack, or in a basket, suspended to the roof of the school, in the

sight of all the pupils, who frequently smile at the birds in the

cage”—emphasis his.

—

Given this unattractive glimpse into Lancaster’s personality, it may

come as little surprise that he alienated allies as quickly as he made

them. A major reason he left Britain for the United States, in fact,

was that rumors had surfaced that he’d whipped some of his young

monitors for his own amusement, and his English benefactors

effectively gave him the boot. This group, the British and Foreign

School Society, acquitted themselves perfectly capably in his

absence, working with missionaries to establish Lancaster’s schools

abroad. They soon appeared throughout the Caribbean, in Egypt,

Malta, Australia, Sierra Leone, Madagascar, the Cape of Good Hope,

and even gained a foothold in India and Ceylon (now Sri Lanka).

Attempts to introduce the system in Germany, Switzerland, and

Holland faltered, but it achieved meteoric growth in Latin America.

Demand for public education accompanied the Latin American

revolutions of the 1820s, and students braved the possibility of

being impressed into passing armies as they walked to their

monitorial schools, which popped up in many major South

American cities as well as in Panama and Mexico.

In the United States, meanwhile, Lancaster made short work of

estranging his friends as he bounced from state to state, always in

search of a new position befitting his genius. A timely missive from

South America arrived just as he was wearing out his welcome in

Baltimore, and he set off for Caracas bearing the invitation of Simón

Bolívar, the revolutionary hero. Upon arrival, Lancaster was given a

welcome befitting a visiting dignitary, and, when he met and

married a woman there—the widow of a long-lost acquaintance—

Bolívar delivered the wedding toast. El Libertador and Lancaster

soon had a falling-out, however, and the latter found himself back

on the road with his new family in tow: to Trenton, to Montreal, to

Philadelphia, always leaving a trail of unfinished projects and angry

benefactors in his wake. “Lancaster was always planning great

things and never doing them,” writes the education historian Carl

Kaestle. “He probably petitioned more famous people for hand-outs

than any man of his day; the list includes Roberts Vaux, Gulian

Verplank, Andrew Jackson, Martin Van Buren, DeWitt Clinton, and

George IV.”

In 1838, Lancaster was trampled to death by a runaway horse in

New York City. Bell had died six years earlier at the age of seventy-

eight, and was interred with great ceremony in Westminster Abbey.

Even before their founders’ deaths, however, both Bell’s and

Lancaster’s systems had begun a long slide into disuse. By the

middle of the century, cities around the world were replacing

monitorial schools with institutions that would feel far more

familiar today, with classes organized by age, not proficiency, and

self-contained classrooms taught by adults, in which every student

was expected to proceed at the same pace.

There are a few plausible explanations for the worldwide

downfall of monitorial education. In the United States in particular,

Lancaster’s “pauper” schools took on something of a stigma. As one

unnamed New England critic put it as early as 1832: “The sole merit

of [Lancaster’s] plan is, that it saves money…I can easily imagine

that such a school may make excellent sailors and soldiers; for they

are expected to be automatons. But for republicans, for freemen, for

self-controlling, and elevated masters of their own destiny—it is not

the place.” The glee with which Lancaster approached punishment

only reinforced the idea that his schools might be acceptable for

other people’s kids, but were hardly a place you’d aspire to send

your own. “We certainly can afford something better,” the critic

wrote.

By the 1840s, it was becoming clear that that “something better”

would consist of self-contained classrooms taught by professional

teachers, an approach championed by Horace Mann, Massachusetts’

first education secretary and an influential advocate for public

schools. In a preview of the economic and cultural changes to come

in the Progressive Era at the turn of the century, established social

structures had been falling away as interstate commerce, abetted by

new railroads and canals, undercut many a local, proprietor-owned

business. In an effort to take up some of the resulting slack in both

social authority and social services, states embarked upon a frenzy

of institution building, establishing poorhouses and hospitals,

mental asylums and prisons. Early in his career, Mann had

personally poured his energy into both a major insane asylum, as

they were then known, in Worcester; and, in Boston, the New

England Asylum for the Blind (known today as the Perkins School).

To Mann’s ideological cohort, a widespread system of public schools

would be the one institution to rule them all: capable of churning

out the sort of Americans who would rise above the general ferment

and govern the young United States wisely.

The question Mann and his compatriots faced, then, was how

not merely to build a better system of education, but to build the

right sort of system, which would produce citizens, not partisans; a

generation motivated by public spirit, not self-interest. Lancaster’s

schools, with their students crawling all over one another in a

constant scramble for advancement, couldn’t have been less suited

for the job. No, what was needed was a flat sort of institution,

capable of providing children with a common set of experiences.

One particularly appealing model could be found in the

professionally led classrooms that prevailed at the time in Prussia

(part of present-day Germany). As a popular book proselytizing for

that model argued in 1836, “The masters of our primary schools

must possess intelligence themselves, in order to be able to awaken

it in their pupils; otherwise, the state would doubtless prefer the

less expensive schools of Bell and Lancaster.”

By the late 1840s, monitorial schools in even the Lancasterian

redoubts of New York City and Philadelphia had begun

supplementing their monitors with apprentice teachers, who

eventually replaced them outright. Soon, students at these once-

monitorial schools were being taught solely by professionals. And

thus the U.S.’s monitorial movement, Kaestle writes, “ended with a

fizzle, not a bang.”

But it didn’t end only in the United States. By the 1850s, virtually

everywhere the tide of monitorial education had spread, it receded.

In fact, given how widespread and comprehensive the turn away

from monitorial education was, its downfall couldn’t possibly have

been the result of any one source of external pressure. Rather, it

makes sense to think of the collapse of the monitorial approach

almost as a technological failure: a breakdown somewhere along the

line where the internal machinery of the system (mainly student

teachers working for free) rubbed up against the demands of the

world outside. Even if permitting students to follow individualized

trajectories through school was a good idea in the abstract, in the

real world of the eighteenth and nineteenth centuries, it simply

wasn’t practical to set up such a system that was simultaneously

cost-effective (in fact, monitorial schools frequently ran less

efficiently than advertised), instructionally effective, and—crucially

—stable for the long term. The rare monitorial schools lucky enough

to have uniquely talented, committed headmasters lasted longer

than most. But every engineer knows that when you’re designing a

system for long-term stability, you can’t count on luck. The

unavoidable fact was, to enable students to move freely through the

curriculum, you needed something on the order of one instructor

per student, and the only way to make that happen at a reasonable

cost was to have students teaching one another for free. But that

hinged on students showing up to teach—by no means guaranteed,

especially as competing, paying teaching gigs became more

available—as well as parents accepting that much of their children’s

time would be spent on the instruction of their fellows. All told,

perhaps what’s more surprising is not that the system failed, but

that it persisted as long as it did.

ANDREW BELL’S DREAM: A POSTMORTEM

In the United States today, nearly every state has a public school

named after Horace Mann—fifty-four in all. Among historical

figures who were neither presidents nor founding fathers, only a

handful can claim so many schools. The Rev. Dr. Martin Luther

King Jr. has seventy-eight. The Marquis de Lafayette, the French

general whom Andrew Bell spotted in Virginia, has seventy-nine.

Neither Bell nor Lancaster can claim a single one.

By the turn of the twentieth century, when the first generation of

experimental psychologists began to think seriously about how to

use the new science of the mind to improve education, the system

they’d inherited was a classroom-based, age-graded one. For the

foreseeable future, students would pass through such schools on a

predetermined schedule, catching as much education as they could

along the way, like carousel riders reaching for rings. John Dewey,

in his short-lived laboratory school, flirted with softening the

temporal edges of this system. The administrative progressives who

won the day, however, saw no reason to challenge the self-contained

classroom in their quest to standardize education and sort students

by their supposed aptitude.

In a different world, perhaps—a world where the name “Andrew

Bell” graced school entrances—students might simply have sorted

themselves, “graduating” from a given course whenever they

demonstrated near mastery of it. But we didn’t, and don’t, live in

such a world. In our world, the vast majority of students, in all their

varied, individual glory, are expected to move along at the same rate

in every class. Today, we continue to rank them based in great part

on their performance in classrooms that may be moving too fast or

too slow for them at any given moment. We remain unable to say

how they might fare at a more optimal pace.

Even the TEAL classroom, despite the fact that it was designed to

meet the cognitive demands of learning minds, suffers from this

unfortunate fact. For instance, in the old lecture format, Peter

Dourmashkin said, cramming then forgetting was the norm, despite

its cognitive drawbacks. TEAL has helped counter that impulse

somewhat, but “we still have that problem a little bit,” he said. “That

problem hasn’t gone away”—because TEAL is still part of a larger,

time-centric whole.

If an approach as radical as TEAL can’t break the spell of time-

centrism, perhaps it can’t be done—at least, not within the confines

of our inherited educational structures. Outside such structures,

meanwhile, wild, new things would presumably be possible. But

there’s no need for conjecture: In fact, a variety of new schools are

now springing up that are not only pushing the limits of education

as we’ve inherited it, but leaving them behind entirely. And that’s

where we’re headed next.

- VII -

OUTSIDE IN AND AT SCALE

In the science fiction novel The Hitchhiker’s Guide to the Galaxy,

there exists a simple, unitary solution to “the Ultimate Question of

Life, the Universe, and Everything,” as its author, Douglas Adams,

put it. After mulling over the Ultimate Question for seven and a half

million years, an absurdly overpowered supercomputer spit out a

perplexingly pithy answer: the number 42. The solution meant

nothing to the cosmic scientists who built the computer, but it did

expose a fatal flaw in their reasoning. They realized, too late, that

they had never defined what the Ultimate Question was, exactly—

and it turned out that an answer without a question wasn’t much of

an answer at all.

To two young humans back on the real Earth, however, 42

represented the answer to a problem that felt just as weighty, albeit

far easier to pinpoint, since it followed them around like a personal

raincloud. The working world, they understood, demanded

credentials of higher education, but the right degree, not to mention

the right training, was perpetually out of reach.

For René Ramirez, a bachelor’s degree in biology at San

Francisco State University had proven elusive. His senior year, he

had already been on academic probation when his grandfather died

and René took on some breadwinning responsibility for his family.

The new stressor pushed his grades over the edge. When the

university told him he could pay an extra $3,000 for a remedial

course that might or might not set him back on track, he bailed. A

follow-up effort at San Francisco’s City College proved just as

unsuccessful. By his early twenties, he was beginning to wonder if

he would ever be able to cobble together a degree.

Josh Trujillo was also scrambling for answers. He’d recently

completed an undergraduate program in entrepreneurship at

Florida State University, but his first business, a healthcare startup

he’d begun in his second year of college, was in a death spiral. The

biggest problem, he later said, had been his lack of technical

expertise in coding and web design, which his entrepreneurship

major had omitted. It seemed like another round of college might be

necessary if he ever wanted to launch a successful tech startup, a

prospect that sounded both expensive and demoralizing.

Near the end of 2015, both René and Josh were weighing their

options when they heard of an opportunity that seemed too good to

be true. Xavier Niel, a French telecom billionaire, was opening up a

free coding academy just outside Silicon Valley, where even

complete neophytes could pick up serious coding chops in the space

of a few years for little more than the cost of food. When they

checked the fine print, they discovered that there wasn’t a catch,

exactly, although the school did have a few decidedly untraditional

aspects. But these weren’t troubling enough to dissuade them. If

anything, it seemed like they had traveled as far as they could along

the road of traditional education. Perhaps an uncommon path was

exactly what they needed.

The most obviously nontraditional aspect of the coding school

was its name: the number 42. It was chosen, they found out later,

because it was the answer to the Ultimate Question of Life, the

Universe, and Everything. It also carried a hidden message: Spoken

aloud, the number sounded like “fortitude,” which any successful

applicant would have in spades.

Unlike most other academic programs, 42’s admissions process

took into account no test scores, no letters of recommendation, no

overwrought essays or overstuffed transcripts. Instead, it accepted

all comers into an intensive, twenty-eight-day trial period known as

a piscine—French for “pool”—which permitted applicants to

distinguish themselves solely through performance. Ecole 42, as the

organization’s flagship location in Paris was known, had already

been operating for several years. René and Josh joined the

inaugural piscine at 42’s first American site, located in Fremont, a

city on the edge of California’s Silicon Valley.

Today, several years later, 42 Silicon Valley remains a jarring

place to walk into. The school is contained within a single blocky

building, cloaked in a curtain wall of blackened windows. Earlier, a

for-profit university chain had operated a branch out of the same

building and, at least in terms of its surroundings, the for-profit had

fit in better. For miles in every direction there extends a green-and-

black circuit board of lawns, parking lots, access roads, office

buildings, and big-box stores: an integrated system of economic,

geographical, technological, and cultural forces aligned to promote

driving, spending, and earning. When 42 moved in, however, it

arrived with its own internal logic so distinct from the world outside

that walking across its threshold today feels a little like entering a

foreign embassy.

Its unique perspective only starts with the fact that the school,

free of charge to students, rejects the idea that higher education is a

consumer good to be purchased like a pair of sneakers or a gallon of

milk. It also rejects the surrounding area’s car culture: Most

students sleep in dorms across the parking lot from 42’s academic

building, but spend the bulk of their waking hours at school, and eat

their meals there as well. Add in the fact that the admissions

process demands no input from the outside world, and a picture of

semi-perfect isolation begins to emerge. Monk-like, 42’s students

turn inward, toward the blackened edifice they call home.

Which, upon closer scrutiny, is not entirely wrapped in smoked

glass. A horseshoe of white concrete that wouldn’t look amiss at

Stonehenge spans the entrance. Inside the cavernous main

workroom, too, rows of empty white doorframes extend in different

directions, rising like croquet wickets above the students seated at

desktop computers. To 42’s student body, they represent the

school’s academic gates, which continue long after admission. 42’s

entire curriculum is arranged in sequential stages, like a video

game, and the only way to advance is to turn in an acceptable coding

project. Students proceed thus, stage by stage, along one of several

available paths, which are twenty-one stages in length. At the time

of this writing, although a few students are getting close, no one has

ever finished level 21—not in Silicon Valley or in 42’s other twenty-

odd global franchises, financed by wealthy individuals and

governments around the world. Before they can make it so far, 42’s

students tend to be drawn away by attractive job offers—a

remarkable outcome, given that many enter the program knowing

not a single line of code.

Today, 42 Silicon Valley’s students have found jobs at almost

every major local tech company and many lesser-known startups.

Part of this ongoing success may have to do with the fact that the

piscine selects from the start for dogged, insightful workers. But

there’s more to it than that, and it likely has to do with 42’s stage-

by-stage structure. The scheme is an example of a pedagogical

philosophy that, in other schools and contexts, can sometimes

produce outstanding results, but which is either difficult to pull off

consistently, or else costs so much to run, that, in its hundred-plus-

year history, it has rarely been seen in the wild.

In “mastery learning,” as the approach is known, the premise is

simple: You don’t advance to Concept B until you’ve demonstrated

total command over Concept A. Test scores serve not as a means of

comparing you against your classmates, but rather as a way to

determine whether you’re ready to advance. And the bar is set high:

in some versions of mastery learning, at a score of 90 percent or

more. The modern name was bestowed upon the scheme in 1968 by

the educationalist Benjamin Bloom. Similar approaches, however,

had found different champions, with different motivations, at

different times in history. An ur-version of mastery, for instance,

prevailed at Bell’s and Lancaster’s monitorial schools, which

permitted students to advance through curricula at their own pace.

Later, in 1919, a superintendent in Cook County, Illinois, created the

mastery-based “Winnetka Plan” in response to the then-ascendant

systems of grading and advancement. Later still, in the 1950s, one of

B. F. Skinner’s chief selling points for his teaching machines was

that they enabled a mastery-type progression: freeing students from

the tyranny of the classroom clock (at the low, low price of chaining

their attention to their desk for hours on end).

Today, mastery is experiencing something of a resurgence. More

than forty schools in New York City have instituted mastery-based

systems as of 2017, and schools in Vermont, Maine, New

Hampshire, Illinois, and Idaho are either following suit or testing

the approach. Success stories abound: For instance, after instituting

mastery learning in 2014, one struggling New York City school saw

its percentage of students reading at grade level jump from

7 to 29 percent in two years. But for every result like this, there is

the unavoidable rejoinder that virtually any change made in

overburdened classrooms could be beneficial. And meanwhile,

concerned parents rightly wonder if modern mastery learning

systems, many of which require students to spend lots of time

seated at desktop computers, are little more than updated versions

of Skinner’s teaching machines, with their purported pedagogical

benefits really serving as a stalking horse for their cost-efficiency.

Mastery learning, however, is just one of several possible routes

to personalization. Hiring a highly skilled personal tutor, for

instance, is one effective, albeit expensive, way to create a

personalized learning trajectory. Various outside-in aligned forms of

education offer other, similar routes: with close enough oversight

on the part of teachers, it’s possible for students to learn what they

need to know while following their own interests at their own pace.

The rub, in both cases, is that they don’t scale well. Even if cost were

not an issue, both tutors and successful child-centered schools rely

on exceptional teachers—which is a problem. I firmly believe that to

the extent that human flourishing exists in this world, we mainly

have exceptional teachers to thank. But exceptions, by definition,

are the sort of thing you can’t count on when you’re working at a

population scale.

Now, however, a small but increasingly influential set of tech-

enhanced approaches is expanding the realm of the possible. 42 is

just one of several outside-in-leaning programs that are developing

technologies in an attempt to deliver broad, deep, activated

knowledge in a way that is cognitively user-friendly, personalized,

consistent in terms of quality of instruction, and, in theory, scalable.

In 42’s case, its scaled-up personalization comes from a hybrid

pedagogy: it bolts the sort of project-based approach beloved by

discovery learning advocates onto a programmatic curriculum. As

its students work their way through, they “level up” not via

multiple-choice tests, but rather by figuring out how to build

increasingly complex edifices of code.

Because the projects 42’s upper-level students complete are

similar to the challenges they will encounter in the working world,

the approach promises job-ready skills. It was this offer—of not just

another academic credential, but rather real coding superpowers—

that led Josh and René to uproot their lives and move into 42

Silicon Valley’s dorms for its first-ever piscine. What followed was

twenty-eight days of red eyes, caffeine, cafeteria food, and unbroken

work. Although the piscine was spread over a far longer period than

any single, standardized test, the clarity of what the school offered,

plus the piscine’s cost in time and effort, made the stakes seem

somehow bigger—as gargantuan as the concrete gate straddling the

building’s front entrance. And so, at the end of the piscine, when

both Josh and René were denied admission, the blow felt more

crushing than either had thought possible.

PLANET CLAIRE

Three hundred fifty miles to the south, in Los Angeles, Claire Wang

was seated in the rear corner of her eighth-grade classroom, reading

a book by herself while her teacher led the rest of the class through

one of its daily lessons. She already knew most of what the teacher

was going to say—not the exact wording but the gist of it. Claire had

already read each of her textbooks cover to cover, twice, in the first

two weeks of school. If she wanted, she could have aced her final

exams there and then. And so her teacher let her spend class time

paging through books of her choice: Ron Chernow’s biography of

Alexander Hamilton, say, or Michael Chabon’s novels. That same

year, she’d taken the SAT twice. She’d gotten a question wrong each

time, but if you combined her best quantitative and verbal results,

she had a perfect overall score. It was around this time that—bored

with traditional academics, despite the best efforts of her teachers

to accommodate what were, it was becoming clear, dizzying

intellectual powers—she’d begun to get serious about exploring the

limits of her brain.

Two years earlier, she’d starred on the Lifetime TV show Child

Genius, a hybrid reality/quiz show where twelve young students

answered difficult questions in a battle for a scholarship. They also

were asked to perform feats of memory, and Claire, who finished

third overall, discovered that she could memorize the order of a full

deck of cards fairly quickly—something many untrained adults can’t

do, even with unlimited time. Curious about her own abilities, she

started frequenting online forums where memory athletes discuss

tactics.

Memory athletes, she discovered, often don’t have any major

innate advantages in terms of working memory capacity. What sets

them apart, rather, is how they use their working memory: less as

temporary storage dump and more as a loading depot where they

can efficiently match new information with deeper representations

—usually, imagined places. Using the method of “loci,” as the

technique is known, athletes tasked with memorizing a deck of

cards will mentally place a given card (say, the jack of hearts itself,

or else a visual mnemonic representing that card, such as Jack from

the movie Titanic, clutching a human heart) at a location well

known to them (such as their childhood bedroom’s doorway). The

key to memorizing and recalling such data points in sequence is to

string several such mnemonics along an unchanging route through

one’s house or neighborhood, and then to mentally walk that route.

In such fashion, for instance, one memory athlete has memorized pi

to more than 65,000 digits.

With such strategies under her belt, Claire soon fought her way

to the top tier of competitive memorizers. The summer after eighth

grade found her at MIT, competing in the USA Memory

Championship.

Each of the day’s trials would cull a few of the thirteen

assembled athletes from competition. They hastily memorized and

recalled 300 words in order (three athletes eliminated), then 40 bits

of personal information about four strangers (three more

eliminated), and then were quizzed about huge quantities of

information gleaned from sources like the periodic table and the

Rock and Roll Hall of Fame, which they had studied in the previous

months (four eliminated).

By the final competition—memorizing a double deck of shuffled

cards in five minutes—only three athletes remained. One of them

was the thirteen-year-old from Los Angeles.

She finished third overall. When the competition ended, local

journalists descended, notebooks in hand. A few talked to the

champion, but most milled around Claire, whose youth made for

irresistible human-interest value.

The next morning, eating breakfast with her family at their hotel,

Claire laughed about the whole thing. She’d begun branching out

into other forms of extracurricular academics, including online

courses and memory competitions, because school had become

stultifying. “Everyone has to learn the exact same thing,” she said,

and it doesn’t matter “if you already know algebra—you have to

learn algebra for two more years.”

But contemplating her next school year, her spirits remained

high.

“I’m going to Ad Astra,” she said.

As in: the secretive school co-founded by tech billionaire Elon

Musk, housed at the SpaceX headquarters in Hawthorne, California.

—

To get to Ad Astra, heading south, you take a right at the structure

that looks at first glance like a grain silo, and then drive for the

better part of a mile, keeping the row of white oil tanks on your left.

The silo, on closer scrutiny, is actually the first stage of SpaceX’s

Falcon 9 rocket, a 156-foot-tall booster that famously touched down

as gently as a falling leaf for a first-of-its-kind vertical landing in

2015. The seeming oil tanks, meanwhile, are in fact a single,

unbroken cylinder used to test the scale model of the Hyperloop, a

high-speed train that avoids air resistance by traveling through a

vacuum tube. Both ventures, as well as the electric car company

Tesla, the brain-computer-interface endeavor Neuralink, and

assorted other ventures, are headed by Musk.

Nestled in among the mile of SpaceX buildings, behind two

layers of friendly security guards, a towering hedgerow, and a form

guaranteeing you won’t post any pictures to social media, sits Ad

Astra.

There’s one other hurdle every visitor must face. The second

security guard hands you a sheet of paper labeled “Polis,” which

features 120 multicolored squares arranged irregularly. Each square

represents a neighborhood dominated by one or more political

parties. “In a way that is ethically sound,” the instructions read,

“your task is to draw five electoral districts.”

One might assume, given its proximity to Musk and SpaceX, that

there is something overwhelmingly high-tech about the school. Not

exactly. More than anything else, what sets life at Ad Astra apart is

the fact that its forty-five students are constantly embroiled in these

sorts of elaborate games: what Ad Astra’s co-founder Josh Dahn

calls “simulations.” Dahn invents them all—he describes the process

as “just maniacally producing content”—and they can range in

duration from less than an hour (Polis is on the shorter end) to

longer than a month. Often, students, working in groups or as

individuals, are involved in several at once.

A warm October day several months after the memory

championship found Claire and the rest of Ad Astra’s students

embarking on an eight-week-long simulation named “Moses,” after

Robert Moses, the “master builder” of New York City, who made

twentieth-century urban planning decisions that advantaged

wealthier New Yorkers, frequently at the expense of residents of

color. Projected in front of a central meeting room was a game map

comprising rows of empty hexagons. Ad Astra’s sixteen oldest

students—none older than fourteen—sat rapt while Dahn explained

the complex rules, which involved a convoluted land-bidding

process. Claire leaned over to whisper to one of her teammates, her

eyes fixed on the map. Finally, when Dahn gave the signal, the

students scattered into glass-walled, satellite conference rooms to

strategize. Almost immediately, one kid emerged and asked Dahn if

it would be okay to spy into other teams’ conference rooms.

Dahn considered for a moment. “That’s not in the spirit of the

game,” he said.

“But we can still do it,” the student ventured. Dahn raised an

eyebrow, and the student turned on his heel and ran back to his

group. The question was a good one, because the lines separating

game play from real life at Ad Astra aren’t always clear. For

instance, in addition to their academic schedule, personal projects,

and simulations, each student maintains a trove of virtual currency:

the Astra. Alone or in small groups, they develop business concepts

to earn more. Three times a year, the students hold a bazaar where

Astras change hands wildly. The students run the entire enterprise,

and their duties include coding the marketplace’s digital exchange

as well as coping with Dahn’s imposed tax system.

His students momentarily occupied, Dahn took a minute to

explain. He pointed to a poster for the upcoming event. “Right above

us here, this is the Ad Astra lottery, which has become this really

controversial piece. Like, should they be allowed to have a lottery?”

It’s up to the students to decide, although Dahn and the other

teachers encourage them to think through any ethical

contingencies. In addition to floating contentious gambling

schemes, students pay each other to redesign their companies’

logos, recode their websites, and manufacture merchandise. One of

the more surprising side effects of the Astra has been the

development of bequests. “There was never a policy created as to

what happens when someone graduates,” Dahn said, “so companies

have been passed down with different amounts of money.”

Once, when Dahn came to MIT to give a talk about game design,

he began describing a simulation he’d made where turning a

monetary profit would account for 40 percent of students’ success.

One of the researchers stood up and asked point-blank why he was

incentivizing students to turn a profit at all. Dahn was astounded.

“Do you really think, in the real world, that profit is less of a motive

than 40 percent?” Working the forces of capitalism into his

simulations, instead of creating simplified conditions, “just feels

more real,” he said.

And activated knowledge, leading directly to influence over real-

world outcomes, is the ultimate goal of Ad Astra. More than a

hundred years earlier, in his Laboratory School, John Dewey had set

up a microcosmic society of students and encouraged them to take

on adult-like working roles: not to study for the benefit of some

hypothetical future self, but rather to strive for success in the

present. Such an approach has a few intrinsic benefits: It can

encourage the curiosity of youngsters better than external

motivators like letter grades and gold stars, especially for those

unable or unwilling to delay gratification. Best of all, knowledge

learned in such settings comes already contextualized for real-world

application.

Through its complex simulations, Ad Astra does something

similar, though with two key modifications: It assumes a state of

advanced capitalism in the world it models (some may find this

cynical, others pragmatic), and it assumes a leadership role in that

world for its students. If, at 42, you work your way through projects

like a character in a first-person video game, at Ad Astra you often

hover high above the game board, assuming the role of politicians,

city planners, and business leaders. In the adult world, “people who

have done great things can really be awful people,” said Dahn. The

school’s mission is not just “to prevent that, but to actively work in

the other direction”—to churn out future leaders, yes, but ones who

are “imbued with some sense of morality, thoughtfulness, and able

to take respect of others into account.”

Put so starkly, it may sound like the two approaches—life on the

game board versus life above it—stand in opposition, but that’s not

quite right. Rather, they represent two prongs of a single outside-in

push to stem the wastage of human potential perpetrated by

standardized education as we know it. In the same way that you can

increase the value of a fraction by taking from the denominator or

adding to the numerator, educators can expand access to learning by

recapturing students unfairly deemed unfit by the educational

winnower, while at the same time removing the unnecessary fetters

imposed on even the most obviously talented students, such as

Claire.

Which isn’t to say that every one of Ad Astra’s students would

have survived the traditional winnower. “One of our most

remarkable students, who got a full-ride scholarship to the top all-

girls high school in the city,” said Dahn, had been overlooked for

years. Only when she nearly won a national scholarship for “gifted”

kids did her teachers and parents realize her hidden abilities. After

she performed so well, her mother wondered aloud to Dahn, “I don’t

even know what giftedness means. What does that mean? Is my

daughter gifted?” He smiled sadly. “It’s like, your daughter is, by any

measure, exceptionally gifted in a traditional sense, and beyond

that, she’s an amazing, remarkable human.”

Failing to invest in someone with unmistakable capabilities is

one of the most head-slapping errors a society can make. Such

students, said Dahn, are “a natural resource”—people we need, now

more than ever, to work on the many problems encroaching on

humankind. The question that arises with these sorts of eager

young scholars, then, is how to avoid tripping them up as they

construct their personal tree of knowledge. They have demonstrated

the ability to absorb great quantities of challenging information,

presented in virtually any format. (In fact, in Claire’s case, that

ability includes a knack and willingness to memorize reams of

unstructured, encyclopedic data.) In such rare but powerful cases,

the enemies of learning begin to look less like the standard nuts-

and-bolts challenges posed by forgetfulness, confusion, and mind-

wandering, and more like issues that arise higher in the cognitive

high-rise: boredom, burnout, and even, if things go wrong for too

long, resentfulness of the very experience of school.

Today, Claire seems to be clear of these pitfalls. Seated at a

worktable near Ad Astra’s outdoor basketball court, she was

ebullient. “Well, right now, I’m taking, like, hard classes. I’m taking

calculus,” she said. Specifically BC calculus, a course completed by

fewer than five hundred Americans of Claire’s age each year. In

most courses at Ad Astra, students pick the overarching direction of

their largely project-based inquiry, and then teachers work with

each student to set appropriately challenging goals. As a result, on

any given day you might see fourteen-year-olds collaborating with

seven-year-olds, diving into the same topics at different depths. But

calculus is a little different: only three of the school’s oldest

students take the course, and unlike every other class, it comes with

a textbook. Claire said that, like before, she could still plow through

the textbook in a couple of weeks, but she no longer wanted to,

because her new class lingered on tricky concepts and applications

of the mathematics that strayed far beyond the book’s pages. She

laughed. “I think one of my favorite classes here is calculus. I used

to think math is boring but now our teacher’s amazing. And it’s just

the three of us.”

For the first time in a long time, school is proceeding at the right

pace for her: fast enough to feed her curiosity, but not beyond her

(prodigious) limits. This level of personalization is one important

part of why, when student-centered, outside-in education works, it

can work extremely well.

But Ad Astra is unique: uniquely resourced, with a unique

student body, and, most important, granted uniquely free rein to try

new tactics. “It’s an anomaly because in almost any other world, I

don’t probably create my own school,” said Dahn. “I would never be

given the opportunity. I wouldn’t get the benefit of the doubt, of

being associated with Elon. I wouldn’t have the resources of SpaceX.

I would never be able to hire the caliber of people that we have. I’d

be struggling to sort of evangelize to a group of parents, who are

maybe open to a new model, but skeptical.”

When it comes to the task of unleashing learning potential on a

truly vast scale, however, the things that make a stand-alone school

special can turn into liabilities. Trying to multiply an approach like

Ad Astra’s—utterly reliant on the vigilant energy of a small cadre of

highly skilled teachers—is a recipe for failure, one that leads either

to costs that, without a billionaire’s munificence, fall outside most

communities’ reach; or else a classroom experience that doesn’t

measure up to the original. When you’re talking about outside-in

schools, with their disavowal of conventional classroom structures,

the latter is especially dangerous, because when failure does

happen, it tends to happen quietly. Say what you will about

standardized tests, but they can give you a good indication of when

things in a school have gone horribly wrong.

And in any case, the free hand enjoyed by Dahn and a smattering

of other lucky educators around the world is simply not

forthcoming at a mass scale. Both 42 and Ad Astra, with their

unique customs, rules, and even internal economies, feel like

outposts of alien civilizations, precisely because they’re designed

not to jibe with the norms endorsed by figures like Mann and

Thorndike. And so, like pieces from an Erector set jammed into a

wall of Lego bricks, they stick out—looking out of place while

hinting that there’s another way of doing things.

That continuing incompatibility with the reigning system

remains one of the biggest obstacles preventing such visions from

spreading. And yet, to listen to certain progressive educators, the

time has never been riper for a takeover. The best pathway for this

revolution varies depending on whom you talk to: some hope to

infiltrate and convert old institutions; others plan to sidestep them;

and still others prefer to operate as though the old rules never

existed in the first place. Regardless, a single thread unifies all of

these efforts. Educational technology, heretofore mainly the

province of inside-out, programmatic assaults on learning going

back to Skinner’s teaching machines, has come to holistic, outside-

in learning in a major way.

ON THE OUTSIDE, LOOKING IN

AltSchool, as the Silicon Valley company Altitude Learning was

known between 2013 and 2019, took the idea of outside-in research

almost absurdly literally. High above its classrooms, AltSchool’s

ceiling-mounted video cameras and microphones recorded silently

as children went about their school days. Machine learning

algorithms then trawled the raw video and audio for patterns, in an

attempt to identify classroom practices that could optimize learning.

Although I have qualms about some of its methods—recording

students chief among them—AltSchool’s larger project was

potentially revolutionary. At the beginning of the twentieth century,

when a standardized, tracked vision of school won the day, it

succeeded in great part because it was the most measurable

approach. Comparing Thorndike’s vision of school against Dewey’s

wasn’t like comparing apples and oranges so much as the number of

oranges against the color orange. To an increasingly efficiency-

minded culture, only the countable method made sense.

Today’s world is, if anything, more quantitative, a fact AltSchool

made no attempt to change. Instead, it posed a simple question:

What if we found a way to count the uncountable?

In October 2018, AltSchool’s founder, Max Ventilla, bounded

into a conference room in his company’s brick-walled headquarters

in San Francisco’s SoMa neighborhood. Lanky, bearded, and clad in

a plain T-shirt, he exuded Zuckerbergian tech aesthetics. Mark

Zuckerberg was, in fact, one of the first investors in AltSchool,

which began as a system of centrally run schools, but soon pivoted—

to borrow the local terminology—to a different structure. By 2018,

the organization was operating just a handful of “laboratory”

schools. These informed the development of the broader AltSchool

tech platform, which could be purchased by any school seeking to

lend structure and accountability to the freewheeling business of

personalized, student-centered education.

Ventilla got his start in Silicon Valley at Google. He left to found

the startup Aardvark, rejoined when Google acquired Aardvark, and

then rose to serve as the head of personalization across Google’s

products. Today, he’s one of a small set of ex-Googlers who say they

are taking deliberate aim at the sorts of difficult problems that

Silicon Valley has yet to even dent. In a sense, the internet has long

been like 42: not the coding academy, but the answer without a

question from The Hitchhiker’s Guide. When Silicon Valley

companies, armed with a solution in the form of internet-connected

technologies, began to search for problems to solve, they raced to

claim the easy ones first. Did we necessarily need dog food delivered

by mail, or unceasing updates about the lives of semi-forgotten

acquaintances? No, but such non-concerns were the most solvable,

so they got solved first. As Seth Sternberg, a former colleague of

Ventilla’s at Google, has said, most Silicon Valley products have

started from the position of “building something that’s easy to

build, and you don’t know if people will want it.”

Within the subfield of education technology, Ventilla argued that

the same exact process had been taking place for decades. “I think

the way that we’ve used technology in an education context has

historically been very dangerous,” he said. “It’s been to simplify the

problem to what technology can solve.”

According to outside-in-inclined educators, there’s far more

involved in successful learning than can be easily automated.

Ventilla walked up to a whiteboard and began drawing what looked

like a snail’s shell. “If I go back to Dewey,” he said, “he’s kind of

describing this experiential learning cycle.”

In his 1910 book How We Think, Dewey broke down what he

called “a complete act of thought” into a five-step process:

identifying an open question (what he called a “felt difficulty”),

getting a sense of what might be causing it, coming up with a

possible solution, testing that solution (through actual or thought

experiments), and then either arriving at a conclusion or probing

further. According to this theory—and others like it; several

educators appear to have crossed this same bridge independently—

you undergo this sort of process every time you personally figure

out something new about the world. Today, open the pedagogical

hood of many outside-in-leaning schools and you’ll see the same

spiral shape powering the enterprise. Even traditional schools teach

it in the form of the famous, five-step “scientific method”:\* identify

a question, form a hypothesis, test said hypothesis, analyze your

data, and come up with a conclusion.

To those who, like Ventilla, have accepted the helix of

experiential learning into their life, the problem with most

instructional technologies (with exceptions like Scratch and Logo) is

that they skip steps. Going all the way back to the mechanical

algorithms of Skinner’s bronze-and-wood teaching machines, the

educational software industry has poured most of its energy into the

subsection of the learning cycle that is easiest to automate: the

identification of a problem and suggestion of a solution.

“What ends up happening is you get stuck in little parts of the

cycle where you’re engaging in the learning very linearly and

superficially,” Ventilla said. Knowledge gained in this way becomes

yet another solution in search of a real problem: like the number 42

in The Hitchhiker’s Guide; like the offerings of first-wave dot-com

companies. Unmoored to any “felt difficulty” that the student

actually cares about, it remains as inert as helium gas.

Through its tech platform, AltSchool hoped to support the full

learning cycle. Every morning, teachers printed out a daily “playlist”

of activities for each student to follow, based primarily on her

individual interests and progress, while also making sure that she

didn’t miss any important topics along the way. Most of the time,

students would interact with printouts, not screens, “but on the

backend there’s an actual app that the teachers are creating those

playlists in,” said Ventilla. As each student moved through her

playlist, she and her teacher recorded her progress in AltSchool’s

software.

“I have a seven-year-old daughter who is now in her third year of

one of our lab schools,” Ventilla explained. “She led the last parent-

teacher conference that we had.” It was like a typical parent-teacher

conference—thirty minutes, conducted in the classroom—“except

my daughter is sitting there between my wife and I and across from

her two teachers. She’s got a template that she’s filled out with her

teachers that has nine different things that she’s going to go

through.

“She goes through what are her goals. Some of those are

academic, some of those are non-academic. They’re set and

displayed in an app that we built. She goes through what progress

she’s made—and that is a mix of her reflection, teachers’ evaluation,

and then standardized grading.”

That last part—the standardized grading—may come as a

surprise, but to Ventilla, it was essential. “We take a nationally

benchmarked, value-based assessment, which shows how much

progress a kid has made in core subjects like reading, English, and

math,” he said. “It’s one of the things I think a lot of progressive

schools get wrong, is they say: ‘You want kids to develop a sense of

self, you want kids to enjoy school, you want kids to be connected to

each other and their community.’ But if that kid thinks that two

plus two equals banana,” he said, his eyes opening wide, “they’re not

necessarily going to end up being well suited for the future.”

At that point in time, in addition to AltSchool’s three laboratory

schools, its platform undergirded one public school system and six

private schools. The laboratory schools stopped at grade eight,

although some of the schools using the AltSchool app ran all the

way up through grade twelve. Graduates’ prognoses were good:

“Over years and years and years, we’ve had every one of our

graduates get into a first- or second-choice school,” Ventilla said.

Selection effects aside, part of the reason may have been the sheer

depth of the transcript compiled by AltSchool’s app, which included

not the sorts of number and letter grades that merely stand in for

learning, but the actual residue of a student’s educational journey: a

portfolio of projects. “They’ve got this layered representation of who

they are and what they’ve done. It lets a school make a much more

confident prediction that that’s a kid who will do well in their

school.”

—

In June 2019, AltSchool pivoted yet again, rebranding as Altitude

Learning. Declaring its research and development phase complete, it

handed away the reins of its laboratory schools and began to focus

solely on its software. The shift raised eyebrows in Silicon Valley

—“Zuckerberg-backed startup that tried to rethink education calls it

quits,” declared the San Francisco Chronicle—and further afield as

well. AltSchool’s swerve provided ammunition to critics who had

wondered if its supposedly holistic approach had merely concealed

the same old reductive thinking, indistinguishable from that of

earlier generations of tech-toting personalizers. Perhaps, as one

disillusioned former AltSchool teacher suggested on his personal

blog, AltSchool’s “playlist”-based system had sacrificed important

aspects of the student-teacher relationship. “It was disembodied and

disconnected,” he wrote, “with a computer constantly being a

mediator between my students and me.” In this line of criticism,

instead of solving the truly “hard problem” of scaling up and

regularizing top-notch, student-centered education, AltSchool had

merely blundered its way into addressing yet another easy-to-solve

part of the problem.

Tidings of Altitude Learning’s demise are decidedly premature.

But at the very least, its travails illustrate the challenges of

shoehorning an outside-in ethos into institutions built on a more

traditional model. On top of everything else, Altitude remains a for-

profit company, and it’s still unclear whether it will convince more

than a few wealthy schools to pay for its platform. And so even if it

somehow were to allay the concerns of its staunchest critics, it

remains to be seen whether it can win enough converts to exert

significant influence at vast scales.

Sometimes, however, the fastest way past an obstacle isn’t

through, but around. Step off the street and into a Wildflower

Montessori school, and you’ll behold an organization with

aspirations every bit as large as Altitude’s, but with no intention to

foist its approach on existing institutions.

—

The first thing you’ll notice when you walk in is how you lower your

voice to match the quietness of the twenty-odd four-, five-, and six-

year-olds in attendance. They aren’t silent—a low hum of activity

and conversation prevails—but there is little shrieking or crying, no

running or fighting. Instead, you’ll notice the young students seated

at tables and on the floor, concentrating on the materials in front of

them. They’re so focused, in fact, that the overall experience feels

like sitting in at someone else’s place of worship. You’re careful not

to let your presence become an intrusion.

About half the students sit by themselves, and half are gathered

in groups of two or three. One kid is drawing with a purple crayon

clenched in his fist, and will continue to do so, imperturbable, for at

least fifteen minutes. Another arranges colorful sticks of different

lengths into a triangular wooden frame. Another boy, who can’t be

older than four, lays plastic cut-out letters onto a floor mat, next to

a column of pictures. A teacher—there are two full-time teachers

and a parent volunteer moving quietly through the room—kneels

down and whispers instructions to him. Later, when he puts away

the mat and the cut-outs and picks up a pencil to start a different

activity, there’s something strange about the scene that you can’t

quite pinpoint. Then it hits you: Never have you seen someone so

young holding a pencil so perfectly.

At Wildflower and other “high-fidelity” Montessori schools—that

is, those that hew closely to the original template laid out by the

movement’s founder, Maria Montessori—students spend two three-

hour chunks of their day playing like this. Or perhaps they’re hard

at work. Or both. To a child constructing an abstracted model of the

world in the glorious, complex, ever-shifting latticework of her

brain, the line separating play and learning isn’t so clear.

Nor, according to the now-hundred-plus-year tradition of

Montessori education, should it be. Maria Montessori’s life’s work

mirrored—and in some ways presaged—that of Jean Piaget, who

conducted observations at a Montessori school for his seminal 1923

book The Language and Thought of the Child, and later served as

president of the Swiss Montessori Society. Both conceived of

learners as active agents running constant information-gathering

routines, not blank slates to be filled with facts, and they even both

went so far as to describe a sequence of developmental stages,

which they thought occurred naturally as children accrued

knowledge. Looking back with the advantage of perfect hindsight,

perhaps the most important difference between Piaget and

Montessori was not of message but of medium: He poured his

research findings into the academic literature, while Montessori put

her observations, collected over the course of decades, into practice

within the walls of the schools that bear her name.

Montessori grew up in Rome, Italy, and, after years studying the

natural sciences, attained a medical doctorate in 1896—an

astonishingly rare achievement for a woman at that place and time.

In the same short stretch of years that, in America, saw the birth

and decline of Dewey’s Laboratory School and Thorndike’s rise to

prominence, Montessori began working with children who had been

diagnosed with forms of mental disability. In Rome, this frequently

meant institutionalization, even solitary confinement, and

inhumane treatment at the hands of attendants, who would

carelessly throw food into children’s barren rooms at mealtimes. As

the education researcher Angeline Lillard has written in her

excellent book Montessori: The Science Behind the Genius,

“Montessori saw in their grasping at crumbs of food on the floor as

starvation not for food, but for stimulation.” To aid them in that

quest, she introduced a set of physical, wooden stimuli and began

teaching her new students how to use them. In 1901, they passed a

national education test intended for students with unimpaired

intelligence, a result that earned Montessori wide renown.

She responded less with pride than consternation; the results

meant most students were capable of so much more. Perhaps,

however, the methods she’d introduced in an institutional setting

could benefit children everywhere. Over the next fifty years, while

her schools spread around the world, she continued to develop,

field-test, and modify her materials and approaches. “Generalizing

her discoveries with unparalleled mastery,” Piaget later wrote—he

understood as well as anyone how science, like learning, involves

the abstraction of general rules from noisy data—Montessori

“applied to normal children what she had learned from backward

ones.” The result was “a general method whose repercussions

throughout the entire world have been incalculable.”

In students’ early years, this method involves extensive practice

with toys that are more than toys, which, at Wildflower’s one-room

shopfront schools, fill shelves on all four walls. These materials

serve any number of discovery-learning purposes: for instance,

enabling students to ascertain essential truths about quantity,

dimension, and the conservation of mass. Although much of the

school day is unstructured, the learning environment is anything

but. The materials are shelved according to ease of understanding,

from left to right, bottom to top, and students let their interest

guide which materials they work with. There is just one overarching

rule: You’re not allowed to use a given object in the classroom until

a teacher or older student has shown you how.

Historically, due to the socioeconomic differences between

private and public school students, it’s been hard to evaluate

Montessori student outcomes in a randomized, controlled trial.

Nevertheless, in recent years, the evidence has mounted in

Montessori’s corner. In 1997, the city of Milwaukee, Wisconsin,

randomly assigned a group of five-year-olds to either high-fidelity

Montessori schools or traditional public schools. The Montessori

students outperformed the traditional students across a battery of

standardized academic tests and behavioral measures—results that

were reinforced in 2017, when a similar natural experiment

presented itself in Connecticut. Perhaps more important, in the

2017 study, an achievement gap between lower- and upper-income

preschoolers closed in the Montessori group, but not in the control.

But the standout result that high-fidelity Montessori preschool

delivers time and again is in the domain of reading and writing.

Anyone familiar with Montessori only by reputation might

mistakenly assume that the system, given its prioritization of

student choice and discovery, would fall into the cognitive disaster

that is Whole Language reading instruction. But in fact, although

Montessori literacy training does rely on discovery learning of a

sort, the overall approach is actually highly phonetic, drawing

crucial perceptual connections between the appearance and sounds

of letters and word chunks. The process begins well before students

even know their letters, with certain Montessori materials, such as

wooden cylinders that students manipulate using a small knob on

top, that train children’s hands for the complex, physically

demanding task of holding a pencil properly. (And suddenly, the

sight of the four-year-old holding his pencil with the confidence of a

much older student begins to make sense.) Materials further along

in the writing sequence develop students’ ability to draw strong

pencil lines, and then, when they are ready, they begin drawing (or

is it writing?) shapes that adults would recognize as letters. With a

teacher kneeling next to them, they learn as they scrawl each letter-

shape to recite certain sounds, which correspond not to the identity

of the letter (aitch) but to its phonetic sound (ha). Eventually,

students line up groups of the letters they’ve been writing and

reciting. With the glow of comprehension in their eyes, they marvel

as “kah-ah-tah” resolves into “cat.” All told, Montessori students

discover their way to reading bit by bit, breaking into manageable

steps a leap that many find too wide to make all at once. The fact

that this process meshes well with everything we know about how

reading works in the brain is a testament to the power of holistic,

top-down research. Many decades in advance, Montessori’s

observations predicted findings that would require years of study

with fMRI scanners to confirm.

Not all Montessori programs are created equal, however. The

Montessori schools that yield the best results appear to be “high-

fidelity” or “authentic Montessori” programs—and therein lies a

major sticking point. The name “Montessori” is untrademarkable,

and the degree to which schools stick to Maria Montessori’s time-

honed methods varies wildly. Consequently, even locales apparently

chock-full of “alternative” schools can be thin on access to Maria

Montessori’s methods.

It was precisely such a shortage in Cambridge, Massachusetts,

that led my friend Sep Kamvar to found the first Wildflower

Montessori school, partway between MIT and the Cambridge Public

Library. Kamvar—yet another ex-Googler involved with search

personalization (and yes, you are sensing a trend)—was working at

MIT, not far from Mitch Resnick, when he needed a preschool for

his two-year-old. He delved into the early childhood education

literature, ultimately alighting on a high-fidelity Montessori

approach. But slots in the local public Montessori school were in

impossibly high demand, and so Kamvar decided to create his own.

Influencing his thinking was not just the writing of, and about,

Maria Montessori, but also the architect Christopher Alexander,

who coauthored a 1977 book, A Pattern Language, that argued that

cities work better when given the chance to develop organically,

shaped by the needs of the people who live there, as opposed to by

city planners in the mold of Robert Moses. In the book, Alexander

and his coauthors raised the idea of a multitude of tiny, “shopfront”

schools, open to the street, that could simultaneously cut

administrative overhead while breaking the architectural spell cast

by large schools—which, the authors wrote, carry the “trappings of

control.”

When prime shopfront space became available in Cambridge,

Kamvar moved quickly, establishing the first Wildflower location.

The effort was a repudiation not just of standard pedagogical tactics,

but also of the idea, going back to Horace Mann and beyond, that

learning belonged in big, centralized institutions. Wildflower’s

commitment to decentralization is also one of the major differences

separating it from AltSchool. The organizations share founders with

remarkably similar backgrounds, funding sources (the Chan

Zuckerberg Initiative, for instance, has been an important source for

both), and a great deal of pedagogical philosophy. They’ve also both

experimented with overhead sensors and machine-learning

algorithms in a handful of schools functioning as living laboratories.

Kamvar even served as an advisor to AltSchool. But where

AltSchool, now Altitude, strives to fit into existing schools,

Wildflower is designed to spring up in the gaps between them, like

dandelions emerging from sidewalk cracks.

Indeed, Wildflower schools spread using the same process that

allows plant roots to defy the best-laid plans of city planners

everywhere: mitosis. Each Wildflower school contains the seeds of

its own reproduction in the form of two Montessori-trained

teachers. Whenever demand for seats exceeds capacity, the school

simply splits like a dividing cell. One teacher remains, and one goes

off to found another school nearby. It’s possible to see this

biological growth pattern in maps of Wildflower’s nationwide

distribution. Wherever a founding school once stood alone, a cluster

of schools now exists. They can be found, predictably enough, in

wealthy coastal regions like Boston, New York, Washington, D.C.,

and the San Francisco Bay Area, but hubs have also popped up in

Minnesota, Indiana, and San Juan, Puerto Rico.

The overall effect is a system of schooling that is, at least in

theory, poised for exponential growth, while remaining cost-

effective, quality-tested, and equitable.

Wildflower schools are designed to be “actively anti-racist,” said

Alison Scholes, who helps coordinate the organization’s expansion

in Massachusetts. “There are a lot of kids in our classrooms who are

coming in from low-income backgrounds or backgrounds with

trauma, and are able to close that so-called achievement gap in a

way that a more traditional preschool, or some of the other early-ed

environments, haven’t been shown to do.” Part of the benefit stems

from the fact that an individualized approach is inherently

cosmopolitan: a student might choose to practice sound-spelling the

word car, for instance, but she could just as easily choose pez—the

Spanish word for fish, swimming in the tank in the back of the

classroom. Wildflower is also pushing cultural inclusivity in more

active ways: “We’re hoping to support an Afrocentric school in

Roxbury getting started this fall,” said Scholes, sitting in a cafe

around the corner from Wildflower’s Dandelion preschool in

Cambridge. “The art on the walls will look different than maybe the

art on the walls in Dandelion, and different from Violeta, which is

our Spanish-English bilingual school.”

For schools hoping to achieve such inclusivity at scale, leanness

is a top priority. As of 2019, Cambridge’s public schools run at a cost

of $29,000 per year for each student (the state average is $16,000)

and local preschools cost between $12,000 and $18,000 per year. By

contrast, Wildflower schools in Massachusetts run at a cost of

between $12,000 and $15,000 per pupil, despite paying their

teachers competitively. Some parents pay that full amount out of

pocket, although many benefit from need-blind admissions and

financial aid. But even the full ticket price represents an

improvement over many traditional preschools and primary schools

in the area. A major part of Wildflower’s relative leanness has to do

with the fact that Montessori schools have always had a higher

student-to-teacher ratio than traditional schools, since students

with free rein to follow their interests require less overt governance.

Wildflower’s small facilities are also easier to maintain than a

traditional school’s, and its testing costs are nonexistent. And,

crucially, it lacks the administrative personnel required to run a

school of several hundred or thousand students.

With that lack of administrative superstructure comes the risk—

present in all schools but especially dangerous in outside-in

programs where student progress is difficult to quantify—of wide

variation in quality of instruction. Wildflower flattens out

inconsistency in part by forming oversight coalitions within its

hubs, and insisting that each individual school’s board include a

teacher from a neighboring school. But qualitative measurements,

too, can provide a perfectly strong measure of whether a given child

is doing well. Montessori teachers have always kept exceedingly

detailed notes of each child’s progress: a paper version, essentially,

of Altitude’s electronic record-keeping software. Through such

records, it’s possible to see whether children are meeting important

benchmarks.

And then there’s the surveillance technology. Wildflower, like

pre-2019 AltSchool, has outfitted a few of its schoolrooms with

overhead recording equipment, which, combined with tiny

Bluetooth trackers in students’ footwear and the Montessori

classroom objects, constantly feed data to remote computer vision

and machine-learning software. Eventually, Wildflower’s research

team hopes to create an objective, quantified data set that will mesh

with teachers’ detailed record-keeping, adding to the sum of what

Montessorians know about learning in their schools.

This approach, put simply, poses stunningly difficult engineering

problems. It’s hard to say when, if ever, machine-parsed data of this

sort will provide insight that human record-keeping cannot, or if it’s

even worth the risk that supposedly “anonymous” student data

might somehow be misused. Regardless of whether this particular

vein of research ever turns up pedagogical gold, however, in a

broader sense Altitude and Wildflower are still both on to

something: scaling up a form of personalized education that strives

to keep teachers at the center of the student’s intellectual life. As

Ted Quinn, Wildflower’s head of research and innovation, put it,

personalization-minded technologists in the inside-out tradition are

usually trying, one way or another, to “automate the teaching

process. That’s definitely not the bet we’re making. We’re keeping

the human in the loop.”

If you pull back and squint at the larger conversation

surrounding personalized education, what Altitude and Wildflower

have done is defined a tradeoff. If, on one hand, you want to see

personalization at scale, but don’t put much stock in the

experiential learning cycle, then you can probably build a self-paced,

automated system for information delivery. But if, like Dewey,

Montessori, and Piaget, you believe that the learning process is

actively driven by the student’s questing mind—an object of

astounding complexity—then it’s necessary to meet that mind with

an object of equivalent complexity. At present, only another human

mind fits that bill. Only concerted human effort can improve on

what, say, a textbook alone can do. And now, for the first time, we

are glimpsing the rise of teacher-powered, scalable education

systems designed to do exactly that. Systems that might someday, at

least in theory, re-create Claire Wang’s calculus breakthrough,

millions of times over.

—

And, strangely enough, we’re also witnessing the rise of an

experiential-learning approach that defies all the rules. According to

the tradeoff defined by Altitude and Wildflower, 42, lying low in its

Silicon Valley office park, shouldn’t work. It’s built on a project-

based, discovery-learning model, and yet it has almost no teachers

to speak of.

When Josh and René were denied admission to 42, it came as a

crushing blow. In the month they’d spent on campus in the piscine,

they had glimpsed a tantalizing picture of themselves, wielding

control over the invisible realm of ones and zeroes underlying so

much of the visible world. But even if either was upset, there was

literally no else one to blame. As Gaetan Juvin, the head of

pedagogy at 42 Silicon Valley, later explained, 42 was designed from

the start “to automatize everything.” It has no admissions

department. There is no dedicated tech support for the hundreds of

computers and twenty-four-hour servers running in each location.

There are no textbooks. And, at least in the way that most people

think about them today, there are almost no teachers.

Or perhaps everyone is a teacher. As 42’s students work their

way through their coding projects, they turn to each other both for

help and assessment. If the scheme seems familiar, it should: It is

as close as anything I’ve seen to the second coming of monitorial

schools. Although 42’s pedagogues hadn’t set out to copy the work

of Andrew Bell, a similar set of founding conditions—including a

munificent benefactor whose resources were large but not

unlimited—led to a similar solution. There is one key difference,

however: 42’s students teach each other not the facts inside

textbooks, but rather how to solve problems. When a student in the

midst of a coding project encounters a “felt difficulty,” as Dewey put

it, she looks for the answer in the project’s accompanying materials,

or Googles for it. If that fails, she asks a neighbor. The thornier the

problem, the more students begin to gather around, surrounding

the irritant like nacre in an oyster’s shell. At a certain point,

someone grabs an advanced student to weigh in. Only the most

intractable obstacles make it all the way up to a teacher—but this

hardly ever happens. Of the twenty staff members that support the

thousand students at 42 Silicon Valley, only four are teachers.

Nevertheless, the system appears to run stably. Its secret is

closely related to why 42 is sealed off so tightly from the outside

world. It’s become common to think of the relationship between

student and school in economic terms: The student is a consumer of

education, sold by the school. But selling knowledge is different

than selling other things. “If I sell you a bottle of water,” Juvin

explained, “then I don’t have the bottle anymore.” But when he sells

you a fact or a hint to a problem, he retains a copy for himself.

Consequently, in a mostly closed system like 42, when students

help each other solve problems, the local repository of institutional

knowledge only grows.

A similar, albeit more formalized, economy prevails over

assessment: If you want a more advanced student to grade your

latest project, you must pay them a chit, which you can only earn by

turning around and grading the project of someone less advanced

than you. This mechanism isn’t just cost-effective; it also forces

students to revisit past subjects with some regularity, the better for

long-term recall. 42’s cognitive benefits don’t stop there: just the

right level of challenge greets students with each new project, a

recipe for continued curiosity. And as they teach each other, they

exercise neural pathways involved not only in the encoding of

information, but also in its retrieval.

All told, virtually all of 42’s idiosyncratic rules and customs

correspond to benefits found somewhere in the cognitive high-rise.

These customs—not to mention 42’s ladder-like system for

advancement—can make it feel almost like a benevolent cult. And

like any cult, once you get involved it can be difficult to stay away.

The piscine that Josh and René failed was the school’s first.

Before launching its third piscine, the school reached out to offer

them another chance. The same rules applied—twenty-eight days of

hard labor—except there was another wrinkle. This time, there was

no spare room for them in the dorms.

They leapt at the chance. To afford a nearby Airbnb, Josh sold his

car. René opted instead to sleep in his, which irritated his lower

back until Josh took pity and let him move in with him. If anything,

they worked harder this time, spurred by their knowledge of what it

would take to pass. And finally, at the end of twenty-eight days, they

earned the right to walk through the first gate.

—

Today, as the receipts from inside-out cognitive science laboratories

continue to come in, it’s remarkable to watch them vindicate certain

outside-in learning strategies. Meanwhile, for the first time,

outside-in pedagogy is starting to look tantalizingly scalable. But

perhaps the greatest surprise, coming out of 42, is the idea that

project-based learning can serve as the key to achieving scale.

In some subjects, that is. Coding lends itself well to a project-

based structure, since code is ultimately checkable: Either it works

or it doesn’t. Other topics, however, lend themselves to different

approaches, and sometimes, a bare-bones, inside-out strategy can be

more effective. Sometimes it may make sense to delegate “some

shallow drill-and-kill style of practice” to an automated system, said

Ventilla. “It’s not that I think that stuff is a total waste.”

The dividing line demarcating where it’s appropriate to invoke

such systems is on the move, however. Recent advances in data

analytics and machine learning, combined with scientists’ continued

forays into the dark regions of cognitive science, are contributing to

a new picture: an inside-out route to mass education, running

parallel to the new outside-in road staked out by schools like Ad

Astra, 42, AltSchool, and Wildflower. Already, a number of deep-

pocketed organizations are developing ways to meet each student’s

unknowable cognitive complexity not with another human mind,

but rather with sufficiently advanced algorithms. And, to the delight

of some (and consternation of others, justly worried about

unintended consequences) it’s showing signs of catching on.

\* A “method,” it’s worth mentioning, that professional scientists often eschew.

- VIII -

TURN IT INSIDE OUT

For anyone who hopes to make learning more effective for far more

people, both outside-in and inside-out approaches now offer real

possibilities. We’ve seen how outside-in thinkers, armed with new

technologies and organizational structures, are attempting to

replicate top-notch learning practices for sizable numbers of

students.

The inside-out strategy of taking successful learning, breaking it

open, and reverse-engineering it has shown its drawbacks, however.

Most disconcertingly, the approach involves a hard-to-assess degree

of risk. A hundred-plus years ago, E. L. Thorndike and his allies

thought they’d reduced learning down to its constituent parts,

leaving no important gear or sprocket unaccounted for. It turned

out that they had oversimplified matters considerably, and the

education system built on their blueprint proved reductive: a crude,

pixelated rendering of the reality of learning. They had jumped the

gun.

Despite the wealth of scientific knowledge we’ve amassed since

then, today’s inside-out thinkers face essentially the same blind

leap: Do we finally know enough about how learning works to build

a better system from the ground up? After all, the cognitive science

of learning is still replete with questions not just unanswered but

unknown. Add in still more open questions concerning how

individual brains fare in any number of different contexts—social,

economic, nutritional, sleep-deprived, bathed in stress hormones,

you name it—and you’ve got more than enough uncertainty to give

all but the most reckless inside-out educators pause.

And yet the inside-out approach has a few intrinsic advantages,

too. First, because the outdated educational structures we hope to

improve upon were themselves built on an inside-out ethos, it’s not

unreasonable to assume that they will more readily take to inside-

out repairs, like a surgical patient accepting a kidney from a close

relative. Second, once you’ve stripped something down and can

explain it from the inside out, it becomes substantially easier to re-

create it at scale. A film photograph might be more beautiful than a

digital photo, depending on whom you ask. But only a digital camera

can strip a complex scene down into numerical values of red, blue,

and green, creating an image file that can be reproduced over the

internet with no delay, with no diminishment in quality, at

essentially no cost.

And finally—and tantalizingly, and controversially—at a certain

point in their technological development, inside-out strategies tend

to meet, then exceed, outside-in approaches. You can simply do

more with a smartphone camera than a film camera. A similarly

stripped-down approach to inside-out education might very well

present pedagogical opportunities we can’t yet anticipate.

It was for all of these reasons—but especially the last one,

dangling the possibility of as-yet-undreamt-of improvements to

education—that when the time came for MIT to make a concerted,

institutional bet on just one route to better learning, we shoved our

chips toward “inside-out.” We wouldn’t just become the purveyor of

online educational materials, including a new library of full-fledged

courses. We would go even further and establish a pipeline from our

community of researchers, within the cognitive science disciplines

and beyond, into educational practice. We closed our eyes, gritted

our teeth, and rolled the dice.

THE MONGOLIA INSTITUTE OF TECHNOLOGY

In the years following that decision, millions of students have

benefited, as will many more, I hope, in the years to come. Included

in the very first group of these learners was a young high school

student living in a high-rise in Mongolia’s capital city, Ulaanbaatar.

“I was in the ninth grade and I was really extremely into math

and science,” Battushig Myanganbayar later explained between bites

of shawarma at MIT’s student center. “But the high school

curriculum in countries like Mongolia and Russia is a bunch of

math drills. You will never understand why you’re solving certain

equations. You don’t even have any clue about how it’s being used

in real life.”

Battushig’s school had one advantage, however: Enkhmunkh

Zurgaanjin, MIT’s first-ever Mongolian alumnus. By late 2011, now

serving as principal of Battushig’s school in Ulaanbaatar, Zurgaanjin

received word of his alma mater’s foray into something known as

MOOCs. The funny-sounding acronym, which stands for Massive

Open Online Course, was first coined in 2008, and became a

household term—in a nerdy subset of households, anyway—in 2011,

when Stanford launched three open online courses.

In December of that year, the arm of MIT concerned with

MOOCs, known as MITx, announced its inaugural entry: Course

6.002x, or Circuits and Electronics. Zurgaanjin encouraged his

students to take the free course in their spare time and, when he

mentioned that it would help explain how an iPhone worked,

Battushig’s ears perked up. 3G internet had recently arrived in a big

way in Mongolia, and by then even nomadic families living on the

steppe had internet access. Battushig’s mother, a doctor, and his

father, a manufacturer of carpets, had brought smartphones into

their home, and they stood out as the sort of thing whose secrets no

one would ever willingly give away. Along with nineteen other

students, Battushig signed up.

Back in Massachusetts, shortly prior to the course’s launch, I

was hustling across campus when I ran into Anant Agarwal, the

professor of 6.002x, who was spearheading MITx’s overall effort

while also running MIT’s famous Computer Science and Artificial

Intelligence Laboratory, or CSAIL. We were both sleep-deprived: I’d

been commuting to and from Singapore every couple of weeks, and

Agarwal had been working into the night for months. I was excited

to find out how the MITx effort was shaping up, and asked him how

many students he expected to sign up for his course.

“I hope no fewer than five thousand students because that would

be embarrassing,” he said, laughing, “but no more than ten or

twenty thousand, because I’m losing sleep as it is and I might die.”

When Course 6.002x launched in May, 155,000 people

registered.

Of these, 23,000 stuck around long enough to attempt the first

problem set, Battushig among them. He spoke only limited English,

and found himself struggling to keep up with Agarwal at times, but

whenever Agarwal switched to the more universal language of

mathematics, Battushig discovered he could follow “just based on

the equation,” he said. After learning each topic, in a manner that

would have made Andrew Bell proud, he turned around and

recorded an explanatory video in Mongolian for his schoolmates.

When roughly 9,000 students passed the midterm, Battushig

was one of them. When just 7,000 passed the course, Battushig was

one of them as well.

Ultimately, of the 150,000 who initially registered, only 340

received a perfect score. Battushig was one of them, too.

Not long after the results came in, a journalist from the New

York Times Magazine came calling to interview Battushig for a

piece ultimately titled “The Boy Genius of Ulan Bator.” And not so

long after that, Battushig, now a local celebrity, began filling out

university applications.

As Battushig’s future began to unfurl before him, so too did the

possibilities for MOOCs. This new form of decentralized, self-paced,

online learning seemed capable of saving, or even recalling, untold

numbers of people from the capricious reach of what I’d begun to

think of as the educational winnower. As Agarwal later said, MITx

has built an eager audience, including “people that are just not able

to go to college”: a coalition of the unduly winnowed who, for any

reason—geography, career, family, age, health, prior test scores, or

something else—have found college’s demands either

insurmountable or too costly.

If MOOCs held great potential for individuals, their capacity for

releasing latent talent on a population level was unquantifiable. For

every Claire Wang, labeled “gifted” at an early age, there must be

hundreds, perhaps thousands, of powerful learners gliding along

under the radar undetected for any number of reasons. For societies

around the world hoping to solve deep, abiding problems, finding

and supporting them was every bit as important as optimizing the

education of students like Claire. As the evolutionary biologist

Stephen Jay Gould wrote in 1979: “I am, somehow, less interested

in the weight and convolutions of Einstein’s brain than in the near

certainty that people of equal talent have lived and died in cotton

fields and sweatshops.”

I find this idea extremely affecting. In fact, what I find just as

motivating as the world’s “lost Einsteins,” as they’re widely known,

is the loss of folks who might not be once-in-a-generation geniuses,

but would nevertheless benefit immensely from an abiding

relationship with learning, and would put their knowledge to worthy

use. Assuming, that is, they’re not prematurely winnowed, like I so

nearly was.

In fact, from the standpoint of solving big, world-sized problems

such as climate change, almost more concerning than how I was

nearly winnowed were the circumstances of my salvation: not at the

hands of kindhearted monks or nuns or educators-qua-educators,

but by an oilfield service company. That job undeniably changed my

life for the better, but at the same time, the urgency of climate

change highlighted the need for more diverse sources of education

and technical training. And so part of what captivated me and many

other observers about MOOCs was the idea that they might open up

new avenues to activated learning for people who might, say, want

to work on a solar installation someday, and not an oil rig.

As MOOCs’ early cheerleaders soon found out, however,

reaching the world’s learners would require more than merely

tossing them a life buoy in the form of online courses—even top-

notch, free ones. Complicating matters, meanwhile, were the

legions of new entrants in the larger field that had become known

as edtech, of which MOOCs constituted only one part. Within a few

years, edtech had become volatile, sloshing with venture money and

populated with thousands of companies ranging from tiny startups

to venerable giants. That was fine, as far as it went: great things do

tend to stagger out of primordial stews. Perhaps inevitably,

however, a subset of these companies developed instructional

systems much farther out on the inside-out end of the spectrum

than MOOCs, evincing worrying levels of confidence in their models

of the learning brain. History has not been kind to hubris in

education, and although public opinion was smiling on edtech for

the time being, it was one fiery wreck away from changing its mind.

I remained convinced that a new, highly personalized, inside-out

education system was technologically possible. We weren’t there

yet, however, and now external pressure was beginning to mount.

SANJAY 2.0

MIT’s push toward free personalized learning has roots stretching

back at least to the late 1990s. First, in 1997, professors Eric

Grimson and Tomás Lozano-Pérez created an online version of their

introductory computer science course for their students. To my

knowledge, this was the first of its kind to interpolate video lectures

with exercises—a structure that is now a mainstay of MITx courses.

Next came OpenCourseWare (OCW): a wonderful, radical idea that

came about at a tumultuous moment in internet history, when,

prior to the first dot-com bust, a number of major universities tried

to turn a profit by selling their brand-name education online. It was

supposed to be “an absolute goldmine,” recalled Hal Abelson, a

computer science pioneer and one of OCW’s founders, and MIT had

arrived late to the rush. In an effort to figure out whether other

universities’ quasi-private model was worth copying, the Institute

hired not one but two management consultancies to do the math—

an idea, I’d be remiss not to mention, belonging to one Dr. Gitanjali

Swamy, then a consultant at one of the firms, who happened to be

married to yours truly. Both firms waxed pessimistic, but one raised

an intriguing suggestion: Instead of selling educational content

online, why not give it away for free?

Most faculty members loved the idea—myself included. The

years following my hasty departure from the North Sea oil platform

were perhaps less cinematic than those that had come before, but

they were a hell of a lot more enjoyable. Once, I’d had to hold my

eyelids open with my fingers as I slogged my way through

mechanical and electrical engineering textbooks. In the model of

the world I’d constructed in my head, each new fact had aligned

only haphazardly against its fellows. Learning had been like trying

to fill a dumpster with oddly shaped automotive parts. Without a

sense of how it all linked up, the pieces’ funny angles and sharp

corners only jutted and scraped against each other in ways that

seemed to take up unnecessary space. Now, however, not only did

the pieces interlock in a way that made sense, but that experience

made it easier to add on to the whole. And so, post-oil-platform, my

time spent poring over books—and increasingly, the internet—felt

entirely different, and far more pleasant, than my prior studies.

That wasn’t all. Earlier, anytime I wanted to add to or amend my

constructed pile of engineering knowledge, I’d always had to dredge

up various, shallowly learned principles in order to marry new

information to the overall structure. This effort had always imposed

undue cognitive load on my precious working memory at precisely

the moment I needed it most. Thanks in great part to the spacing

and interleaving and retrieval practice I’d been subjected to in my

industry training, however, fundamental engineering and physics

principles now sat at my fingertips. I could wield such facts as

though they were part of me: powerful tools to be used in the

construction of yet more knowledge.

It was with this new brain—Sanjay 2.0!—that I began to sail

through my studies for what felt like the first time since middle

school. On the helicopter ride off the platform, I began to plot my

return to the academy. I assembled the coursework I’d need to apply

for a master’s, which—it all seems so quick in retrospect—led to a

PhD in mechanical engineering and, ultimately, a job offer in the

Department of Mechanical Engineering at MIT.

Along the way, I began to teach and, inevitably, to recognize the

challenges of life on the other side of the podium. When you’re

responsible for just yourself, it’s hard enough to overcome

learning’s malevolent rogues’ gallery: the not-quite-right

explanations, the misunderstandings, the confusion and

forgetfulness and cognitive load limitations. It’s quite another,

however, to straighten out such snafus in someone else’s brain.

Learning, I now knew from personal experience, didn’t have to be a

battlefield. Even predating my time in the oil-flecked wilderness,

there had been rare moments when learning had come easily: for

instance, when I’d had the chance at university to build a snake-

shaped robot, the thought of which still makes me unaccountably

happy. But such fleeting moments had always felt like the

exceptions to the pattern. Most of the time, I’d understood learning

to be a ruthless, competitive business, red in tooth and claw and

teacher’s pen—and, despite my best efforts to prove otherwise,

many of my students seemed to agree.

Then, in 1997, I was invited to help teach Course 2.007 with

Alexander Slocum, the legendary professor who inherited it from

Woodie Flowers. That year’s robotics contest was sports themed,

with robots vying to push balls and pucks onto their opponents’ side

of an intervening divider. (I still remember how that year’s winner,

the tanklike Fuzz Bumper, belonging to one Timothy Zue, prevailed

over significantly more complex opponents.)

Course 2.007, I began to recognize, did something curious. With

its project-first structure, it helped students contextualize

engineering far more effectively than a traditional lectures-plus-

exams setup, because whenever they encountered a “felt difficulty”

in the lab, as Dewey put it, they turned to the lecture content for a

solution. And meanwhile, as they built their robots over the course

of the semester, they could hardly avoid repeatedly revisiting

knowledge that they had filed away earlier in the course—

benefiting, as a result, from both spaced repetition and retrieval

practice.

Perhaps even more important, the hothouse atmosphere of

Course 2.007 made the apparatus of the educational winnower feel

like an afterthought. For once, students were competing for

something grander than a high GPA. In fact, because the semester-

end contest had no direct bearing on students’ grades, it appeared to

have a freeing effect, permitting students to take risks, make

mistakes, and learn from those mistakes in a way that’s not possible

when your permanent transcript is on the line.

Even while 2.007 was drawing knowledge into my students with

an almost capillary action, I had to acknowledge that the same thing

was still happening to me. One day, I was talking to my colleague

and close friend David Brock, a roboticist who worked down the hall

from me. For years, a bulky, expensive system of electronic

transponders, known as RFID tags, had been used around the world

to track shipments of vehicles and other large inventory items.

Brock wondered if they could be simplified significantly (and made

so power-efficient that they wouldn’t need batteries) by stripping

down all the data they transmitted to just a single number, and

hosting the rest of it on the internet.

My eyes must have opened to the size of teacups, because I

realized that if such super-simple RFID chips could be produced,

then perhaps they might be produced absurdly cheaply. In that case,

they could be used not just to track massive things moving around

the world’s supply chains—cars, shipping containers, cattle—but

small ones as well. I did a bit of approximation, Mahajan-style, and

determined that simple, passive RFID chips could be made for less

than ten cents apiece (in fact, they would later be manufactured for

less than three cents), cheap enough for my purposes. And just like

that, the next decade-plus of my professional life dangled before me,

assuming I could figure out how to grab it. If I did, I might create

something of lasting value for essentially everyone, since it would

drive down the retail price of goods, including food, benefiting both

suppliers and consumers.

Together with other partners, Brock and I quickly set up a team,

called the MIT AUTO-ID lab, devoted to stripped-down RFID

technology. One member of the lab, Kevin Ashton, opened our eyes

to possibilities posed by super-cheap RFID not just for global supply

chains, but also for local inventories. It could be used to keep track

of every book in a library, every box in a warehouse, every sweater

at The Gap. Such a technology would even make possible a “smart”

anti-theft device, now quite common in retail shops, capable of

sounding an alarm only for unpaid-for items. (Ashton also famously

coined the phrase “the Internet of Things” to describe a world of

increasingly interconnected objects.)

The only question was how I would learn everything necessary

to make it all work. I busied myself with the task of making RFID fit

the needs of different types of users, which necessitated speed-

learning across sprawling domains. I hustled to understand not just

the electrical engineering and computer science principles

underlying RFID, but also the prevailing concerns of semiconductor

manufacturing, the worldwide logistics business, and tech startups.

We worked with startups to develop the physical tags, and others to

make a better, cheaper tag-reader device. We cozied up to corporate

giants, who could champion our protocol over others. I personally

started up a company to create the open-source, cloud-based

software that the new RFID tags would reference. This all required

learning on a scale I had never attempted before, and I won’t

pretend it wasn’t difficult. But this time, I knew how to do it. I didn’t

always know where everything would go on my schematic tree at

the start, but I now knew I was capable of making it fit. So I drank

coffee, put in my late nights, huddled with colleagues, and, over

time, modern RFID came together. Today, it’s no exaggeration to

say that the world runs on our system. Billions of RFID tags are

now used globally: in retail, in supply chains, for highway toll

collection, to find lost pets—even to track evidence in police labs.

MITX

In 2003, while we were hustling towards the finish line for our

RFID standard, a computer server under Anant Agarwal’s desk

blinked to life. Running on it was a quirky little program called

WebSim: the world’s first virtual circuits laboratory. “I was very

excited about online learning,” he later recalled, “but I said, ‘Look,

until I can convince myself that I can do online laboratories, this

ain’t gonna go anywhere.’ ” So he hacked together a program that

allowed his students to tinker with different virtual configurations

of conductors, resistors, capacitors, transistors, and the rest. At the

time, deployment of this proof-of-concept virtual lab was enough

for Agarwal. “I did not take it and put my entire circuits course

online. I did not do that. Shame on me!” he said. Then, in 2008,

Salman Khan, an MIT alumnus whom Agarwal had taught in the

late 1990s, began posting YouTube videos designed to help students

through tricky spots in their studies. This effort, which he turned

into a nonprofit named Khan Academy, exploded in popularity. In

2011, a new entrant appeared. Stanford University, as I noted

earlier, announced that it would offer three open online courses,

which would soon spin off into two for-profit MOOC providers:

Coursera and Udacity.

Once again, as in the late-nineties dot-com boom, MIT appeared

to be a latecomer to a tech-enabled education party. And once again,

MIT would respond by giving away the goods for free.

“MITx was launched on December eighteenth, 2011,” Agarwal

said, rattling off the date like it was his own child’s birthday. Earlier

that year, MIT’s then provost and future president Rafael Reif

convened a meeting of the MIT brass to figure out what to do about

the potentially titanic changes coming to university education. Reif

had long been working to expand MIT’s educational footprint, and

Stanford’s announcements lent the enterprise a new urgency.

At the time, the prevailing plan was to establish campuses in a

number of countries, either built from the ground up or else in

partnership with local universities. The poster child was the

Singapore University of Technology and Design (SUTD), which we

had recently launched with the government of Singapore. I was

intimately familiar with it, since I had been tapped to lead its

instructional design process.

The Singapore project created a rare opportunity to distill MIT’s

core pedagogical principles, which went all the way back to the

beginning. MIT was founded as a more pragmatic, technical

alternative to Boston’s nearby universities, a legacy that the

Institute’s founders memorialized in its motto: Mens et Manus, or

“Mind and Hand.” From the start, it prioritized learning by doing,

incorporating laboratory instruction at a time when rote learning

reigned. As a member of the class of 1868 attested, “The method of

teaching was completely new to all of us. We found ourselves

bidding goodbye to the old learn-by-heart method…We learned from

experiment and experience.” Building a new university from the

ground up in Singapore created the chance to reconnect with these

founding principles. For instance, where MIT insisted that every

student experience two semesters of core courses across the

disciplines before declaring a major, SUTD would have three shared

semesters, a “freshmore year” designed to ground students with a

firm biological, physical, computational, and humanities

foundation. Where MIT made open-ended design courses like 2.007

an option, SUTD made them mandatory across disciplines. SUTD

also cut back on lectures significantly. Instead, TEAL-style

workshops, labs, and studios convened—a strategy only made

possible by the physical environment we were building, which

featured far more open and modular rooms and laboratories than

the typical American university.

After nearly three years, with SUTD self-sustaining, the time

came for me to return to MIT proper, which was weighing its next

move in a world that now contained MOOCs. The mood at the 2011

leadership meeting still favored building bricks-and-mortar schools

in the vein of SUTD. I still remember the exact moment when

Agarwal, by then the head of MIT’s main computer science

laboratory, changed that. Why, he asked the group, are we helping

open small, new campuses in various cities when we could, in his

words, “create a virtual MIT for the whole world”?

It’s hard to predict how groups will respond to challenging ideas.

All I can say is that, by the end of the meeting, it was pretty clear

that MIT wasn’t going to go for it. And then, within a week,

seemingly everyone’s mind had changed. It was like the Institute

climbed out of the other side of the bed, stretched, and decided it

was now time to place a major bet on online learning.

Agarwal began to move quickly. Squinting at the world of online

ed in those days was like standing in the predawn darkness while

giant, foreboding shapes lurched in the distance. No one could say

what tomorrow’s sun would reveal. No one knew which model, for

instance, Stanford would pursue—for-profit or non-; private

partnership or university department; open-source platform or

closed. In any case, it was certain to be big, and within a year or two,

other, similar entities would appear. In such an inchoate world, the

only thing to do, Agarwal believed, was to stride forward and make

our stamp.

It was with such an attitude that MIT announced the formation

of its own MOOC venture. Given the Institute’s recent history of

putting course content online for free, the move raised the

possibility of a world of MOOCs animated by a similar spirit of

openness: free resources available to anyone, perhaps even running

on an open-source platform. Because Agarwal wanted to make this

statement before the MOOC field finished congealing, however, he

had to announce his intentions first and then start building. The

plan hit the internet in December 2011, with the first course slated

to begin in February 2012.

The ensuing scramble to honor the announcement unfolded on

two fronts: designing the platform where MIT’s online courses

would live, and building its first proof-of-concept course. The

former was given the placeholder title MITx on the assumption that

something catchier would eventually come up; it didn’t. The latter,

meanwhile, was originally supposed to be a computer science

course, but every computer science professor Agarwal approached

blanched at the timetable.

Leaning back and rubbing his eyes with the heels of his hands,

he chuckled. Instead of a computer science course as planned,

MITx’s first course would be an introductory circuits course, taught

by Agarwal himself—a job he would shoulder in addition to

developing the platform, which itself sat on top of his nominal

duties running CSAIL, MIT’s largest research laboratory.

This circuits course, he already knew, would feature something

like his own long-neglected virtual circuits lab from 2003, now held

together by little more than digital duct tape. He needed a new one

to accommodate MITx’s likely scale, and that was far from the only

thing that needed building. Happily—in his first act of self-

preservation since the start of the project—Agarwal gathered an

academic murderers’ row of helpers.

“Each of them is like the world’s expert in what they do,” he said.

“Gerry Sussman”—a celebrated MIT computer scientist and artificial

intelligence pioneer—“did all the problem sets,” he said, producing

“amazing, amazing problems.” Chris Terman, a senior lecturer at

CSAIL, built the new version of Agarwal’s virtual circuits lab, and

Jacob White, another professor, built the equation solvers that

powered the circuit simulator. “He can make differential equations

sing,” said Agarwal. Meanwhile, Ike Chuang—a pioneer of nuclear

magnetic resonance quantum computing who would later help erect

MIT’s overarching Office of Digital Learning—built another needed

set of equation solvers. “Ike Chuang—the guy would go away, and

the next day he had a linear equation solver worked out for the

platform. Just like that! So, the circuits course, even to this day, is

one of the most advanced online courses available.”

One thing the course needed that Agarwal had not originally

considered necessary was a brand-new complement of lecture

videos. He’d planned on saving time by resurrecting older videos of

him professing in the lecture hall, but, he said, “my team convinced

me to redo them, and in a weak moment, I gave in.” The new videos

borrowed Salman Khan’s approach: laying down audio recordings

while writing and drawing on PowerPoint slides using a tablet. (The

team found Khan’s work so helpful, in fact, that in some cases, they

decided not to try to improve on the original and simply linked to

his videos.) Meanwhile, they reserved lecture-hall videos for big

blockbuster classroom demonstrations, which, as often as not,

involved the use of a chainsaw in front of a live audience of

students. Perhaps the most maniacal move Agarwal made—and in

retrospect, the most prescient—was to teach the online version of

the course concurrently with the on-campus course, populated with

student volunteers. This decision only worsened Agarwal’s time

constraints, but it conferred certain advantages. For one, it

permitted Agarwal to “flip” the on-campus course: Students watched

the online lectures prior to class, and then came in to run through

exercises with Agarwal and other instructors in person—sessions

that were then videoed and provided as supplementary material

online. The rationale for such a structure is, as we’ve observed,

quite compelling: Students can adjust the timing and speed of

lectures to meet their own preferences, and class time can be spent

actively retrieving information from memory and applying it.

Perhaps more important, the in-person class vouched for the

realness of the virtual one. Like backing dollar notes with gold, the

fact that the on-campus and online versions of the class were

coextensive and equally rigorous lent heft to the latter.

As the semester wore on, stories about the mysterious tens of

thousands of students on the other end of the internet connection

began to roll in. Battushig’s name came to Agarwal’s attention, and

so did that of Amol Bhave, a young man in India who became so

enamored with Agarwal’s course that he turned around and created

an online learning platform of his own. Both would go on to attend

MIT and graduate with flying colors.

MITx, meanwhile, was expanding, and fast. Around the same

time that Agarwal’s circuits course launched, Reif was talking to the

leadership at Harvard. In May 2012, the two universities announced

the creation of a joint, nonprofit venture: edX. This new endeavor

would piggyback on MITx’s software platform, and would soon host

online courses not just from MIT and Harvard (although MITx

would remain its largest tributary), but an ever-expanding list of

colleges and universities.

THE CANTABRIGIAN EXPLOSION

The world of open online learning was off to a roaring start, and for

a breathless moment, speculation abounded that MOOCs’ mere

existence would save the world from itself. “Nothing has more

potential to unlock a billion more brains to solve the world’s biggest

problems,” wrote New York Times columnist Thomas Friedman in

early 2013. Another New York Times article declared 2012 the “Year

of the MOOC,” and it seemed like every year thereafter would be

filled with more video-based online learning than the year before.

And indeed, by the end of 2018, according to the organization Class

Central, which acts as a search engine across MOOC providers, over

100 million students had enrolled in 11,400 courses, provided by

more than 900 colleges and universities around the world.

Within just a few years, however, expectations began to

whipsaw. Enrollment in individual MOOCs, initially an exponential

launch ramp, appeared to stall, due in part to the original hype

fading and in part to the increasing diversity of available courses,

which brought in more students but spread them thinly. Course

completion rates, too, failed to increase over time, which vexed

some observers. (This never bothered me—leaving a MOOC

unfinished is less like dropping out of high school and more like

putting down a long nonfiction book halfway through. Regardless of

how far you’ve progressed, you’ve learned something.) Far more

concerning, however, were the students’ socioeconomic statistics,

which, within a few years, had started to become apparent. Despite

the abundance of heartwarming stories like Battushig’s, MOOCs

seemed to disproportionately benefit relatively affluent populations.

Although other MOOC providers kept their enrollment numbers

close to the vest, edX made its statistics publicly available. As a

series of independent dives into these data revealed, students from

wealthier regions accounted for the overwhelming majority of both

edX’s enrollments (which remained free) and its completion

certificates (which, starting in 2015, began to cost between $50 and

$300).

Despite these sobering results, edX was still demonstrably

helping many learners who, for whatever reason, didn’t fit the

traditional profile of college or graduate student. In terms of age

demographics alone, for instance, edX’s enrollment was on the

older side, suggesting a user base of mid-career learners. In

Agarwal’s very first circuits course, half of the students who passed

were twenty-six years old or more, including one who was seventy-

four years old; 5 percent, meanwhile, were of high school age. It was

clear that people outside the traditional collegiate profile were

flocking to edX. And yet, the world’s poor—the largest group of

would-be learners—were not finding their way to the platform. As a

result, less than five years after MOOCs stepped onto the world

stage to all the fanfare of a Vegas prizefighter, their boosters—

myself included—found ourselves fending off charges that MOOCs

were already, as one Udacity official put it in 2017, “dead.”

In fact, they’re just hitting their stride. As Agarwal pointed out in

2019: “We’re still signing up 100,000 students a week. We’re

signing up more students a week than we’ve ever done in our

history.”

And yet, there was one other reason why overeager observers

still wanted to prematurely sign MOOCs’ death certificate. Even as

MOOC providers continued to plunge forward into the foggy future

of online learning, stranger entities began to shamble out of the

mist.

—

By the mid-2010s, a venture-capital-fueled bonanza was taking

place in the field now known as edtech. New companies were

approaching the industry from every conceivable angle: content

delivery, student finance, testing and assessment, ed research,

classroom management, and many others. In 2018, when one

capital firm attempted to describe the entire landscape, it counted a

total of fifteen thousand companies, which it organized into a map

so complicated, it could have passed for the brain’s white matter.

One nexus of the map, labeled “digital courseware,” is growing

crowded: filling up with tech organizations claiming to promote

learning that is simultaneously personalized and grounded in

cognitive science. A kaleidoscopic variety of approaches is already in

use at schools, homes, and colleges. A school might run flipped

classrooms, for instance, as the Clintondale High School in Clinton,

Michigan, has, by supplementing its home-grown lecture videos

with those of Khan Academy, while hosting said lectures on

Blackboard Learn and Edmodo, a popular learning management

system and an educational social network, respectively. A number of

International Baccalaureate schools around the world now offer

courses taught remotely, with a human at the far end, delivered by

the online provider Pamoja Education, which students take during

set-aside periods of their week. A similar but temporally looser

approach can be seen in the abundance of “virtual schools” that now

dot the United States, which permit students to take most or all of

their classes from home, conferring with teachers online or over the

phone. Schools that value temporal flexibility but prefer to gather

their students in one place, meanwhile, can adopt what’s known as a

“flex” model, letting their students flow through temporally

unstructured days, guided only by software. And so on.

In the variety of approaches now on offer, perhaps the starkest

delineation runs between programs whose students all proceed

through roughly the same content at roughly the same rate

(perhaps with some impressionist blurring at the edges), and

approaches that deconstruct the shared classroom experience into a

Jackson Pollock drip painting of individual trajectories, free along

axes of both pacing and content. Until very recently, advances in

this second, more far-out category were held back by limitations of

the underlying software, which, at its core, was built on if-then

statements of the sort found in Choose Your Own Adventure game

books: To venture into the spooky basement, turn to page 10; to call

the police instead, turn to page 12.

The algorithms that increasingly run much of our lives today,

however, have become far more complex, a trend to which edtech

has by no means been immune. As I mentioned in the prior chapter,

outside-in, research-minded educators like Sep Kamvar and Max

Ventilla have experimented with machine-learning algorithms as a

means to sift through student behavior for useful patterns. They

haven’t yet uncovered much actionable intelligence, but similar

techniques applied to an inside-out framework can theoretically

produce recommendations that any educator bold enough—or

perhaps hubristic enough—can employ immediately.

The most venerable fish in edtech’s machine-learning lagoon is

IBM, which has built its education offerings around its well-known

question-answering system, Watson. In 2011, Watson became a

household name by besting two prior champions on the quiz show

Jeopardy!. The main challenge for the show’s human contestants is

one of information storage and retrieval. Not so for Watson, which,

though disconnected from the internet during the contest, still came

preloaded with a massive corpus, including the entirety of

Wikipedia. The challenge for the IBM team, rather, was the part that

comes easiest to the show’s human contestants: making sense of

the clues spoken aloud by the show’s beloved host, Alex Trebek.

Human beings arrive in this world with brain structures

dedicated to the processing of spoken sounds—which, as you may

recall, are involved in reading as well as speaking and listening. To

use a common turn of phrase, one might say we are language-

parsing machines; except, historically, we’ve been far better at it

than any computer. In the past few decades, however, as available

computing power has increased, machine learning has gone from

theoretically possible to practical, and the computers have begun to

catch up. The idea behind machine learning actually goes back to

the neuroscience theory that proposes that “cells that fire together

wire together,” as the handy phrase goes, first posited by Donald

Hebb\* of McGill University. In Hebb’s theory, variations in strength

among synapses “wiring together” could form the foundation of

memory. More or less contemporaneously with Hebb’s decree,

computer scientists began to think about how the brain’s

probabilistic synapses and neurons could be represented not in

flesh, but in computer code. It’s possible to set up a single virtual

neuron, for instance, that can be trained to “fire” or not (that is, give

a yes-or-no answer) in response to many combined inputs (such as

the individual light-sensitive cells in a digital camera’s sensor). Just

one virtual neuron so designed can be trained to identify whether a

written shape is a given letter or not—a feat remarkably similar to

what the brain’s letterbox appears to do. Artificial neurons’ pattern-

finding capabilities really start to open up, however, when you stack

them in tiers on top of one another, such that the yes-or-no outputs

from each layer train the subsequent layer. Today, “deep learning”

systems can feature twenty or more layers of neurons. In the most

complex of these systems, most of what takes place between input

at layer 1 and output at layer 20-something is fully hidden from

observers. Indeed, this opacity is so complete, and deep learning

systems now so prevalent in our lives, that a group of modern

computer science luminaries have called for the formation of a new,

unified field named machine behavior, to study their effects. In a

satisfyingly cyclical turn of events, the field seeks to apply the

stimulus-response research paradigm of behaviorism—championed

by B. F. Skinner, Thomas Watson, and even E. L. Thorndike—not to

people, but to computer algorithms.

It was one such algorithm, trained to abstract semantic patterns

from spoken English and match them against a deep corpus of

knowledge, that permitted IBM Watson to vanquish the most

redoubtable human competitors on Jeopardy!. While the public was

growing accustomed to its new quiz-show overlord, IBM was

already working to slide its question-answering system into every

conceivable economic niche, in fields ranging from healthcare to

finance to the legal profession to even fantasy football. In 2016, as

part of this push, IBM announced Watson Education.

As of this writing, Watson Education has come out with two

main products, Watson Classroom and Watson Tutor, which are

really Janus faces on the same head, oriented toward teachers and

students, respectively. IBM’s engineers can feed this core system a

corpus of information—say, the content underlying a geology course

—and, in theory, it will parcel that content into individual topics.

“You have to train it to a domain,” said Alex Kaplan, IBM Watson

Education’s global leader of strategic deals. “This,” he said, making a

box with his hands, “is everything that’s known about geology. So

Watson knows all of that. Since it knows all of that, Watson can

draw a concept map of the interrelationship of all the primary

concepts. So now you’ve got this concept map around geology.”

By a few different means—in the case of Classroom, mainly a

classroom’s worth of standardized test data; in the case of Tutor,

mainly questions posed by a text-based chatbot—the core system

then attempts to map a given student’s personal trajectory through

a course’s worth of material.

Tutor, which IBM has developed with the publishing giant

Pearson, is supposed to function like a wise owl, sitting on your

shoulder and answering your questions as you read through an e-

textbook. Once you fire it up, it’s designed to zealously pursue a

single goal: to get you to demonstrate mastery of each important

concept in the unit or chapter, nudging you along with well-timed

questions and hints from relevant passages. (For now, only higher

education and professional students have access to it.)

This version of mastery learning, different from most classroom

mastery schemes, juliennes topics wafer thin. Instead of defining

“mastery” as, say, a 95-percent-or-greater score on a course, or even

a weeklong unit, the system atomizes topics so completely that the

question of mastery becomes not scalar but binary. Either you know

that oxygen is the most abundant element in the Earth’s crust or

you don’t; there is no in-between.

In one sense, technologies of this sort are still a long way from

being even a plausible replacement for human teachers. For the

moment, the thought of a history class taught by even the best

available chatbot—say a circa-2020 Amazon Alexa—is laughable;

job-security-conscious teachers would seem to have little to worry

about. But then again, machine-learning software is so different

from the forking-branch software of yore that the idea of a major

breakthrough seems a matter not of whether but of when.

In the coming years, we’ll be seeing plenty more from whence

Watson has come. The company Squirrel AI, based in Hangzhou,

China, for instance, which helps students prepare for China’s year-

end standardized tests, already serves as many students as all of

New York City’s public school system. It slices its school subjects

almost absurdly finely—reducing middle-school mathematics, for

instance, to 10,000 unique instructional points, which, Pac-Man-

like, students gobble up each according to her own personalized

path. In the future, “human teachers will be like a pilot” of a plane

on autopilot, the company’s founder, Derek Li, told MIT’s

Technology Review, operating mainly as a fail-safe while providing

significant emotional reassurance to the passengers.

Most examples of this sort of inside-out, machine-learning-

powered edtech apply to STEM fields, since their hard edges and

unambiguous questions lend themselves more readily to

automation. This isn’t universally the case, however. In fact,

machine learning has made significant inroads, surprisingly

enough, in the field of essay instruction and grading. It’s been a tale

of some promise and no small degree of peril. Machine-learning

algorithms, trained on human-graded essays, can theoretically cue

in on whatever human graders find good or objectionable about the

essays they encounter, grading huge numbers of essays more or less

instantly. The GRE, for instance, the major graduate school

entrance exam in the United States, utilizes a machine-learning

essay-grading system known as “e-rater.” An internal 2018 study,

commendably made public by the GRE’s parent organization, delved

into what makes e-rater tick (remember, the workings of such

systems remain an unknowable black box, probe-able only from the

outside). The results weren’t encouraging. For one thing, it

appeared to reward longer essays, regardless of how effectively

students used their extra verbiage. (In fact, some students have

begun copying in memorized passages of “shell text” that, though

utterly unrelated to their essay prompt, add length and boost

scores.) Far more concerning, the system assigned lower marks to

African Americans’ essays, in particular, than did human graders. It

was possibly (the authors of the study can’t say definitely) the result

of an issue well known in machine learning: a hint of bias in the

data used to train a learning algorithm becoming vastly amplified

once the algorithm is operating on its own. In the case of e-rater,

human trainers had accidentally created what appeared to be a

racist algorithm.

Machine-learning-powered education software, in some

instances promising and in many others downright dystopian,

makes the strides taken by MOOCs look almost like baby steps. In

MIT’s development of some of the earliest MOOCs, we recognized

that we didn’t know everything about learning, and so we insisted

on keeping humans in the equation: human lecturers behind the

videos; human moderators on the message boards. True, at the scale

we were contemplating, such cozy, face-to-face tactics as discussion

sections became difficult to pull off. But still, if there were some

unknown, vital nutrient necessary for education as we knew it,

perhaps with humans in the online mix we could still preserve it.

The food we were serving up might be prepackaged, but at least it

had once grown in Earth’s soil. Personalized, machine-learning-

powered education programs, by contrast, are more like a lab-

grown, synthetic food, guaranteed to contain every nutrient that’s

known, which is all perfectly fine—unless, that is, it turns out that it

lacks an unanticipated nutrient (or contains an unanticipated

toxin).

And anyway, it really isn’t all that hard to imagine a few ways a

machine-learning-led progression through school could lead to

educational deficiency. By breaking down school subjects into

impossibly small points, a machine-learning algorithm could easily

account for every fact in a curriculum, but not integrate those facts

properly during instruction. Students might thus learn calculus, but

not learn to think using calculus. Worse, if a machine-learning

algorithm were trained specifically to optimize standardized test

outcomes, the system would risk tripping into cognitively harmful

study traps such as massed learning, which leads to good short-term

test results but poor long-term retention. And then on top of such

mechanistic cognitive issues, there still remain all the now-familiar

rejoinders from outside-in educators: even if a student’s rate and

sequence of learning is customized, for instance, that still doesn’t

take into account what motivates her, or makes her curious.

I was mulling these and other problems over when Susan Silbey,

then the chair of the MIT faculty, told me I needed to talk to one of

her PhD advisees.

THE DELTA PROBLEM

By this time I’d taken on a unique role at MIT. Exploring how

learning works, and how best to promote it, remains one of the

most pressing and fascinating questions facing humankind. It

should have come as no surprise, then, that many of MIT’s

departments would find their compass needle of inquiry drawn

toward learning at one point or another. The pursuit pulled together

scientific disciplines in surprising ways, combining the forces of

mathematicians and molecular biologists, linguists and computer

scientists, psychologists and physicists. Broadening the discussion

to include the art of education only looped in more disciplines,

bringing to the table economists and social scientists, teachers and

historians and artists.

It was all almost too big to even think about in one sitting, let

alone do something about—and yet, we had to do something.

Wherever any of the above research disciplines intersected with

learning, researchers were always there, at the front lines, hacking

away at the unknown either from the outside in, the inside out, or

somewhere in the middle. We needed some way, if not to physically

bring all of these researchers together in one room, then at least to

create a framework where their work could coexist and build on

itself.

And so, in 2016, MIT announced that it would be creating a

constellation of interdisciplinary groups all falling under the

auspices of a new unit: Open Learning. Today, Open Learning is

broken into two halves: research and development. The research

side includes MIT’s Integrated Learning Initiative, or MITili

(pronounced “mightily”), led by John Gabrieli, the renowned

neuroscientist. MITili is our Penn Station of learning and education

science, bringing together research threads from all different

directions. On the development side, meanwhile, can be found the

Office of Digital Learning, which produces online learning media

(including MITx courses) for learners on campus and off. And J-

WEL: a separate, newer effort funded by the charitable foundation

Community Jameel, which gathers together best educational

practices from around the world.

The carrier pigeon flitting between all of these fonts of wisdom,

improbably enough, is me: the guy who so enjoyed his university

courses, he took them twice. The position is essentially sui generis,

with no real equivalent at any other major research institute that I

know of, and it’s a tremendous honor to occupy it. The task of

pulling our disparate research threads through the needle’s eye of

real-world practice is sufficiently daunting that I turn to the help of

experts whenever possible. And so, when Susan Silbey, an expert in

the dynamics of complex organizations, told me to talk to her

student, Marc Aidinoff, I immediately opened my schedule.

Aidinoff had a story to tell. As a PhD student at MIT, he had

joined Freedom Summer Collegiate, an organization that brings

doctoral candidates to underserved areas of Mississippi to lead

seminars for college-bound high school graduates. His doctoral

work, a history of how the rise of networked computing has

influenced U.S. social policy, seemed at best tangentially related to

this mission, but what he observed in Mississippi turned out to be

one of the more shocking intersections of computing and

government he had ever encountered. He began to make repeat

visits, now as an ethnographer, seeking to understand what edtech

was doing to schools there.

“It’s really hard to get teachers to the Delta, and the schools are

particularly poor,” he explained—and racially divided. Worse, the

region is suffering from an extreme teacher shortage, exacerbated

by the inability of schools to offer nationally competitive wages. In

1997, the situation was dire enough that the Mississippi legislature

passed a so-called Critical Teacher Shortage Act; today, the shortage

in the region is six times worse, and it disproportionately affects

poorer districts with a higher proportion of African American

students.

To make up for the shortfall, districts have begun turning to

technology. Some of these fixes are as simple as they are

distressing. For instance, Aidinoff described one high-school-level

Spanish classroom that, in the absence of a teacher, simply watched

a video feed of a classroom the next school over. Others are more

sophisticated. It’s become increasingly common to see Delta-region

students sitting in classrooms, navigating digital courseware on

Chromebooks without an accredited teacher to guide them. Instead,

classrooms are staffed with “facilitators” who lack content

knowledge. In a typical classroom period, according to an exposé

produced by Mississippi Today and the independent news nonprofit

the Hechinger Report, students access the online portal provided by

the edtech company Edgenuity, or one of the state’s seven other

approved online vendors. The program guides them through sub-

lessons broken up into segments labeled “Warm-Up,”

“Instruction”—a lecture video—“Summary,” “Assignment,” and

“Quiz”; larger tests come at the end of units.

To be fair, these schools are not using this product as

recommended; it is “designed to work hand in hand with teachers,”

an Edgenuity company representative said in an email. This

approach makes a good deal of sense: online learning tools are

almost always best used in conjunction with human instruction. But

at the same time, the very existence of online-only options can, in

cash-strapped school districts, create ideal conditions for misuse.

Without a teacher in the room, for instance, student questions can

languish unanswered. “We’re just going over some of the facts that

we should know and it’s kind of difficult,” one student told

Mississippi Today. “If I’ve got question to ask, how you do that? I

can’t ask the computer and the teacher that up in there, she don’t

know it.”

Just as concerning, without a content-savvy figure in the loop,

the practice of teaching directly to standardized tests, already all too

common, can become clad in software iron. One reason a school

system might turn its limited budget over to digital courseware

companies is that they sometimes promise good results on

standardized tests. “The principal is faced with a choice between a

teacher, or a company that’s selling either software or packets, often

with a guarantee of some kind of test rate,” said Aidinoff. As a

result, “it’s very common that, for the entirety of high school, you

never hold a book in an English class.” Rather, the digital

courseware feeds you passages that resemble the passages you’ll

encounter on standardized tests. “You’re basically doing SAT prep in

some way, and often repeating the passages multiple days so that

you can get better,” he said. “The students really repeat lessons very,

very often.”

Perhaps the most concerning side effect Aidinoff observed was

how the program transformed the remaining adults in the room—

the non-teaching “facilitator” or “school resource officer”—into

stand-ins for authority, not knowledge. “The expertise the ‘teacher’

has is disciplinary and nothing else, really,” he said. “That, to me, is

the question that most of these programs miss. They forget that

there’s going to be a person. And I’d generally prefer the person

wasn’t functioning as a cop or, literally, a ‘school resource officer.’ ”

—

I still believe in edtech. I believe in its potential to improve human

flourishing: to loop more of us into the world of learning and carry

us farther along profound educational journeys. To amplify the

power of teachers. To nimbly apply both inside-out and outside-in

research findings. To make learning user-friendly across the board,

and therefore more attainable for a wider variety of brains hailing

from a wider variety of backgrounds.

But it’s now clear that any such deliverance will be complicated.

As studies into the effectiveness of MOOCs continue to show,

despite recent, staggering increases in worldwide mobile internet

availability, access alone can’t guarantee that anyone will find her

way to online education. Roughly half of all people on Earth now

use the internet; in India alone, the internet-using population has

multiplied by a factor of thirteen since 2007. And yet, there is a

whole host of reasons why someone with a smartphone or

connected laptop might not take an online course, ranging from

limited free time and energy to the local absence of jobs where a

head full of knowledge can be put to use.

One especially important factor is the question of whether

there’s a human being with content knowledge in the mix. The

students in the Delta region are only part of a larger trend. A sizable

2019 review study conducted by MIT’s J-PAL—a sister organization

to J-WEL that is focused on global poverty, co-founded by recent

Nobel laureates Esther Duflo and Abhijit Banerjee—determined that

students in traditional classrooms tended to outperform those in

online-only courses, although the online-only option was still

certainly better than nothing. However, students in online courses

who also had an in-person instructor performed just as well as

those in traditional classrooms, and when those online systems

created personalized student pathways (particularly in math, often

aided by machine-learning mechanisms), some students performed

as well as those receiving private tutoring—the gold standard for

personalized education.

Even Battushig Myanganbayar, the MOOC poster student, had

in-person help: not just his MIT-alum principal who first directed

him toward Course 6.002x, but also a visiting teaching assistant

from Stanford, who was a friend of the principal. As Justin Reich,

the ed researcher who has led most of the recent independent

MOOC studies I’ve mentioned, has argued, Battushig’s story “isn’t a

story about an individual, it’s a story of the MIT alumni network

and a community of people working together to raise the quality of

education in Mongolia.” The headline of the New York Times article

about Battushig called him “The Boy Genius of Ulan Bator,” Reich

pointed out, but “the story could have been called ‘The Boy Genius

of Ulan Bator and His Very Well-Educated Mentors.’ ” Although any

MOOC is far, far better than no instruction, its powers magnify

geometrically—especially, I think, for younger students—when you

introduce a human being to whom students can pose questions as

they arise.

The J-PAL study does not draw distinctions between the

different types of artificial “cognitive agents,” as the study calls

them, undergirding digital courseware. As the more effective,

machine-learning-endowed exemplars continue to distinguish

themselves, we may see students, particularly older ones, striking

forth as tech-augmented solo learners, and conquering at least some

topics as effectively as those with personal tutors. But no amount of

technological advancement will outweigh the most significant factor

that can make or break tech-enabled learning: its broader social and

institutional context.

Take Course 2.007. One of the harshest lessons it teaches its

roboticists-in-training is that even when a technology always

functions perfectly in the lab, if it doesn’t work in the wild, then it’s

not a successful technology. In the case of edtech, “the wild” must

be understood to include not just well-heeled schools, but also cash-

strapped institutions that find themselves forced to use software—

even against the express advice of its creators—to replace teachers.

Perhaps what disturbs me most about the Mississippi example is

not just how resoundingly the technologies in question fail students

in the Delta region. It’s the fact that the very same technologies,

wielded as a tool by skillful teachers in relatively munificent

districts, could easily have a reverse, beneficial effect. That may

sound like it’s not much of a problem, but it is: Such a technology

could act like a sieve, benefiting the haves and harming the have-

nots. Assuming your underlying goal as a technologist is, like mine,

to raise everyone up, especially have-nots, then such a technology is

worse than a dud. Instead of recalibrating the educational winnower

to be more forgiving, such a technology has the potential to

reinforce its worst biases.

POISONING THE WELL

Educational technologies that harm students today have the

potential to poison the well for better technologies to come. Two

hundred years ago, in the Western world’s first encounter with

personalized, mass education, the existence of substandard schools

run by Andrew Bell’s acolytes and imitators—especially Joseph

Lancaster—lent strength to the odor of charity and poverty already

clinging to the monitorial approach. Such schools, it became clear,

were acceptable only for other people’s kids.

It probably didn’t help that Lancaster, in particular, developed a

reputation for putting most of his energy into creative punishments

for bad behavior. The role of discipline and punishment in

Lancaster’s failed system takes on new, queasy-making life in the

context of today’s Delta region schools, where students work under

the watchful eye of classroom disciplinarians, not teachers. It’s a

recipe for resentment toward all things related to school.

It’s difficult to get a sense of precisely how many schools across

the United States, let alone the world, are replacing their teachers

with digital courseware; there are too many independent school

districts and too many companies servicing them. I’ve asked a

number of onlookers in both the edtech industry and associated

think tanks about the issue, and they have estimated that the

pattern that has appeared in the Delta region probably remains

fairly rare. However, programs that are mechanistically similar,

even if they fit differently into the larger education landscape, are

popping up with increasing frequency. “Credit recovery,” for

instance—an umbrella term for strategies that allow high school

students to make up classes they’ve failed or missed—often hinges

on online courses. Again, it’s hard to say exactly how prevalent the

practice is, and the specific approaches used in online credit-

recovery courses vary wildly, as, presumably, does quality. But it

does appear to be widespread: in 2011, 90 percent of U.S. school

districts engaged in some kind of credit recovery.

As online learning continues to make inroads into school

districts, classrooms, and homes, I’m growing concerned that it will

trigger a public outcry before its full potential can be realized. One

volatile point that’s only begun to come into focus is the matter of

how student data will be used. I don’t mean just the normal privacy

concerns we all have, with unaccountable entities tracking our every

step and selling that information—although the thought of a

shadowy marketplace for children’s behavioral data is especially

creepy. As concerning as that is, I’m even more worried about how

online student data can be fed into the educational winnower—and

how that will in turn affect the well-being of students trying to

learn.

Traditionally, a student’s academic progress has been reflected

by a relatively sparse data set, collected mainly on test days and at

the conclusion of big assignments. But the flip side of the promise

of hyperpersonalized education is the specter of highly granular,

ongoing assessment: the ceaseless weighing, sorting, and ranking of

students. In theory, a course of online study could conceivably rank

students according to everything from their study habits to their

mouse cursor movements to (far creepier still) their facial

expressions. (MITx does none of these things, by the way.)

On one hand, a minimally creepy, continuous assessment regime

might represent an improvement on how we currently sort

students. The twenty-eight-day admissions piscine at 42 operates

somewhat along these lines, and it creates a far more detailed

picture of a student than do test scores and letters of

recommendation alone. But the idea of making every moment in a

student’s day or week a potentially sort-worthy event is deeply

troubling. I’ve already suggested that a certain type of student

flourishes in our traditional educational winnower; perhaps a shift

from sparse to continuous surveillance wouldn’t solve this problem,

just select for a new personality type. More concerning, if a

student’s every click, every keystroke, every failed attempt on a

problem set redounds to her permanent record, then she’ll never

have true freedom to take risks and fail, like the students in 2.007

do. If any future purveyor of a hyper-personalized education system

wants to avoid sacrificing learning for the sake of sorting, they

must, at the barest of minimums, permit students to make mistakes

that are not recorded, never carved into digital stone.

—

If machine-learning-enabled personalization threatens to merely

replace one reductive winnower with another, you might reasonably

wonder whether it’s a technological avenue worth exploring at all,

or if we should just leave it well enough alone. As tempting as that

option might seem, however, it would be a major mistake, if only

because machine learning’s theoretical instructional capabilities

range far beyond the horizons of today’s classrooms.

To pick one fascinating example, take the work of Fox Harrell, a

true polymath who holds a joint appointment at both CSAIL and

MIT’s Comparative Media Studies Department. Harrell produces

interactive, multimedia works of computer art, often powered by

home-grown machine-learning systems, not to mention Harrell’s

deep understanding of cognitive linguistics: one of the more

fractious battlefronts of the cognitive revolution. An important

assumption underlying his work is the idea, borrowed from the

cognitive linguist George Lakoff, that we all rely on nested

structures of cognitive metaphors to make sense of the world. Some

of these are simple and apparently universal, with deep

sensorimotor roots (for instance, the idea of “more” represented by

the direction “up”), while others vary by culture, and still others are

personally idiosyncratic. According to Lakoff’s theory, these

metaphors are a major part of what makes each of our experiences

of the world unique. Harrell’s software artworks are designed to

build bridges across personal and cultural metaphors, to help you

begin to see the world through the lens of someone else’s

constructed reality. It’s a heroic project that is still in many respects

getting under way, and yet it’s an important proof of principle.

Technological systems need not only oversimplify human

experience; they can also complicate one’s education in a way that

might not otherwise be possible. With the promise of such powerful

techniques to look forward to, a general turn away from machine

learning in education would be unfortunate, to say the least.

That’s not really likely, in any case. What’s more probable, to

paraphrase the science fiction novelist William Gibson, is that as

the machine-learning-enabled future arrives, it will continue to be

unevenly distributed. Necessarily, the more a technology diverges

from how education is traditionally done, the less compatible it will

be with existing institutions. It was for this reason, in fact, that IBM

Watson diverted the bulk of its energy from K–12 into higher

education, where the rules are less rigid, and professional

education, where there are no rules at all. (“It is the Wild West,”

said IBM’s Alex Kaplan.) Suppose cutting-edge edtech continues to

develop in this way: forced to grow in the cracks between existing

institutions, in the mold of Sep Kamvar’s Wildflower Montessori

schools, or else in the wide-open spaces of developing countries.

Such a world might well see what’s known as a technological

leapfrog effect: where developing regions race ahead of their more

developed (but also more entrenched) brethren. Leapfrogging

countries skip the landline stage of telephonics and adopt mobile

internet, for instance (something I’ve personally observed in my

own family in India), or jump ahead of clunky electronic money

transfers and set up seamless mobile banking. Could less-developed

parts of the world, and nontraditional students everywhere, armed

with new modes of technology-assisted education, leap ahead of

their more entrenched counterparts?

“It’s already happening,” said Agarwal, now the CEO of edX. In a

Circuits Analysis course at San Jose State University, the classroom

pass rate was 55 percent in 2012. “When they used the edX class on

campus, the pass rate shot up to 91 percent. It leapfrogged.” He

continued, sotto voce: “But we just try to downplay, because it’s very

threatening.” (Meanwhile, adding gasoline to the fire, a concurrent

experiment with a rival MOOC provider did not go nearly as well,

which caused San Jose State’s faculty to revolt—justifiably, in my

opinion.)

Technologists are now hard at work, designing systems

threatening—no, that’s not the right word—promising, sooner or

later, to spread quality education more widely than ever before,

while improving on the status quo wherever possible.

But in the past several years, even as technologies have arrived

with the potential to challenge the caprices of the educational

winnower, the winnower has proven resilient: bending those

technologies that can be bent, and outmaneuvering those that can’t.

And so we find ourselves in an uncomfortable resting place.

Whether your preferred approach is outside-in, inside-out, or some

hybrid of the two, improving learning alone is not enough to fix

education. There still remains a system at work, hell-bent on

designating students wheat or chaff based on factors that still have

little to do with their potential as learners, let alone as human

beings.

Perhaps, if we’re ever going to truly help people everywhere tap

their unrealized wealth of potential, it is time to address the

winnower head-on.

\* And if his name has faded since you first encountered it in chapter 2, it’s worth revisiting

why. If you remembered the general idea behind his model of memory, then, according to

the Bjorks, perhaps competing names, real or imagined, crowded out Hebb’s. Or perhaps

you put this book down for a few weeks and, without continued stimulation, the synapses

involved in your memory representation of the entire fire-together concept became weak

with disuse. Here, happily, is a chance to fire those wired-together synapses back up and

reap the benefits of spaced practice. See if Hebb’s name lingers longer in your memory this

time around!

- IX -

THE SHOWDOWN

It was the second and final day of the Course 2.007 robotics

competition, and Woodie Flowers, the guest of honor, took to the

podium to kick off the event. An oversized cutout of the Death Star

loomed behind him as he surveyed the crowd.

Flowers was normally a sunny personality, but today he had not

come to deliver good news. The state of knowledge in the United

States, he soon made clear, had taken a perilous turn.

“In this country, for example, less than half of the adults accept

evolution,” he said. “We’re doing crazy things. We’re shutting off

the truth that’s associated with science. The EPA is purging

scientists from their governing structure.

“One major thing that’s going on that requires a lot of attention

is the wealth divide,” he continued. “If your parents are in the top

one percent”—he gestured at a slide referencing work by the

Harvard economist Raj Chetty—“you have a good chance of being in

the top 30 percent. If your parents are in the bottom one percent,

strong indication you will be in the bottom 30 percent.” He looked

out over the crowd. “That’s not the way it’s supposed to work.”

Among his audience in MIT’s Johnson Ice Rink—a hundred-odd

Course 2.007 students and several times that in supporters and

alums—sat the thirty-two competitors who had fought their way to

the final event. “You guys have to save us from ourselves,” Flowers

said.

It was late May: that sleepy, valedictory moment in the academic

calendar when speakers attempt to slip the starched overcoat of

generational responsibility onto younger, unsuspecting shoulders.

But if anyone had the right to demand action from his course’s

students, Flowers did, because in a small yet quite literal way, he’d

equipped them for it. In Course 2.007, he had created an

educational oasis where students could rapidly contextualize and

apply engineering knowledge; from which they emerged ready to

exert their will on their surroundings through the medium of

robotics. As Amy Fang, one of the contenders still standing on this

final day of competition, later said: “It’s so tangible, the things that

I’ve learned, and that I can actually apply in the world.”

The audience, meanwhile, was anything but sleepy. In fact, it

was singing with anticipation. Of the thirty-two competitors

remaining, sixteen had scrabbled their way to today’s final

competition via yesterday’s ruthless round robin, into which a total

of ninety-five competitors had entered. These survivors had spent

the night strategizing and making last-minute repairs. Meanwhile,

the other group of sixteen, who for the most part owned the top

robots in the competition, had yet to be tested in public. They had

earned their place via the “Ladder”: tournament slots the professors

had set aside in the weeks prior for those best able to score points in

the lab. This latter Ladder group included Alex Hattori, the former

BattleBots competitor; Z, who had unveiled a robot capable not only

of spinning both cylindrical thrusters but also of delivering a

smaller robot to the X-wing’s upper deck for the purpose of

sabotaging his opponents; and—surprisingly enough, given his early

struggles—Brandon McKenzie, the swimmer.

The clear favorite, though, was Tom Frejowski, a lanky, reserved

Chicagoan with a long history of tinkering in his bedroom

workshop. Like many of this year’s top contenders, he’d designed a

forklike device capable of reaching into the foursquare buttonholes

of the X-wing’s lower thruster and spinning it. Tom’s fork, however,

was uniquely reliable: It was attached to a pliable rubber coupling

that allowed the thruster to spin even if the robot were imperfectly

aligned with the thruster’s face. This neat bit of design, combined

with some highly strategic coding, gave Tom an enormous edge.

Each full, single-elimination competition round would take a total

of two minutes, but the first thirty seconds were designated solely

for robots capable of autonomous action, with no human at the

controls, and any points scored during this period would count

double. Then a tone would sound and ninety seconds of radio-

controlled play would begin. At this juncture, most students would

be just setting out on their quests for points, but not Tom: By the

start of the radio-controlled period, he would have already banked

416 points for spinning the lower thruster autonomously. Then—

and this was the real trick—Tom’s robot would continue spinning

the thruster as the autonomous period gave way to radio-controlled

play, instantly earning him an additional 208 points. As a result, by

the thirty-first second, Tom would already be sitting pretty with a

staggering 624 points on the board—a feat made all the more

impressive by the fact that his robot was, in the words of professor

Amos Winter, “dead reliable.” A handful of other robots could

theoretically amass comparable point totals, but none so

consistently.

There was one contingency Tom hadn’t prepared for, however: a

human one. His name was Richard Moyer, and he had been forced

off the Ladder at the last minute. As a result, he’d had to fight his

way into today’s competition via yesterday’s round robin, which

made him something of a dark horse entrant. But in his very first

round yesterday, jaws had dropped to chests and eyes had fixated on

the scoreboard. His robot, like Tom’s, sauntered up to the thruster

during the autonomous period. Then it fired up a motor that

sounded like a lawnmower—louder than any other 2.007 robot by a

wide margin. The rumor mill soon made clear that Richard had

customized one of the competition’s provided motors beyond all

recognition; it was the only one of its kind.

By the end of his round, Richard’s score was glowing in red: 912

points. Tom wore a tight smile. Still, Brandon, seated nearby, had

wondered aloud whether Richard had sealed his own fate by

designing a robot that relied on a custom-built motor. “That could

burn out,” he’d said, a hint of optimism in his voice. “He has no way

of replacing it.”

—

Even as the final thirty-two competitors took in Flowers’s words,

the mood was one of eagerness, not fear. Regardless of what

happened today, nothing bad would happen to anyone. No one’s

future would suffer if her robot fell apart in a pile, because the

semester’s-end contest had no direct bearing on students’ grades. In

effect, the competitors had been operating in a safe zone of sorts:

free to take risks, make mistakes, and learn from those mistakes.

This sanctum, where excitement outweighs fear, is actually what

enables Course 2.007’s other pedagogical achievements, including

how it motivates curiosity and contextualizes engineering

fundamentals through real-world practice. Rather than add to the

winnower’s existential threat, Course 2.007’s competitive, hothouse

atmosphere somehow makes its lethal apparatus feel like an

afterthought.

In Brandon’s case, that equated to a chance to scrap his erstwhile

scissor robot and start over. “I decided to revisit the drawing board,”

he said. His new robots—plural—looked somewhat rickety, but he

had adopted Z’s direct-drive approach for his new, thruster-spinning

fork, and there was no denying that they made the thruster hum.

Safe in 2.007’s embrace, its students are given an experience that

is, I think, as true to the founding ideals of MIT, set down way back

in 1861, as they get anywhere on campus. The principles of Mens et

Manus, “Mind and Hand,” predated E. L. Thorndike’s influence by

thirty-five years, as well as such institutional fingerprints as credit

hours and GPAs, even federal accreditation of universities. Most

importantly, Mens et Manus predated our supposedly meritocratic,

entirely ruthless, cradle-to-grave system, which was built to enable

winnowing as much as teaching.

Today, as I ponder how to avail a truly effective education to as

many people as possible, I keep returning to Course 2.007. The way

it separates school’s winnowing function from its teaching function

—stripping apart two aspects of education that have been glued

together for over a hundred years—hints at at least one viable way

to rethink the winnower and make education substantially more

inclusive.

THE MICROMASTERS

Taking the broadest possible view, recovering vast quantities of

latent learning potential—not to mention improving a whole lot of

lives—is as simple as optimizing instruction while also improving

access to it. As we’ve seen, however, these two levers often work at

cross-purposes. Some of the most successful attempts to inject

modern cognitive science and personalization into educational

practice come with a lamentably limited reach: extending only to

small, experimental schools, say; or student demographics outside

traditional educational institutions, such as midcareer professionals

or kids growing up in rural Mongolia. Such populations may

amount to a new, untamed “Wild West,” as IBM’s Alex Kaplan put it

—an exciting proving ground, to be sure, but one that leaves behind

everyone already inside the schoolhouse walls.

The challenge before us, then, becomes something of a two-

handed piano improvisation. On one hand, how do you best ensure

that the newfangled educational opportunities reaching those “Wild

West” populations are actually useful; that those students can plug

their new knowledge back into society in ways both personally

remunerative and beneficial to their communities? And on the

other hand, is it possible to expand the borders of this Wild West to

include more learners every year?

I can’t tell you exactly which strategy, if any, will win out for

every age group, in every discipline, everywhere in the world. But at

the very least, I can tell you what we’re doing about it at MIT.

Ultimately, higher education is where MIT wields the most

influence\*—and as it happens, certain types of higher education are

particularly ripe for re-wilding. By 2015, MITx and edX were already

off to a strong start when I began to get the indescribable feeling

that we had a chance to zag while everyone else was zigging. At the

time, MOOC providers, edX included, had begun to dabble in

awarding badges and completion credentials to students, which in

theory allowed them to prove to employers that they’d learned

something. In practice, however, issuing a new, made-up credential

came with the same problems as printing a new currency: They

could only achieve value in the wider marketplace by proving that

they were valuable, a catch-22.

We had one coin of exchange that others didn’t, however. We

could back a new online credential using the bullion of a traditional,

on-campus MIT degree—perhaps the Institute’s most valuable

asset.

We wouldn’t mess with MIT’s bachelor’s degree—in many ways

a sacred object—nor with our PhD. The master’s degree, however,

was intriguing, featuring a number of arbitrarily stuck-together

elements that, with a little care, could be teased apart. What if, I

wondered, we were to crack a master’s program in half, putting the

parts most suited for online learning on the internet and reserving

for campus those parts requiring face-to-face interaction? Those

steps alone wouldn’t actually be all that radical—approaching a

flipped classroom, essentially—but the second part of the scheme

would challenge the established order of things.

An online first half of a master’s degree, I believed—essentially a

highly intensive semester’s worth of courses, delivered online over a

year or more—was a course of study worth certifying in its own

right. This credential, which we eventually named the

MicroMasters, could also do something else, however. It could serve

as the primary admissions criterion for a second, on-campus half of

a full master’s degree. In such an arrangement, we could educate

students by the hundreds of thousands online, and then, for those

willing to go further and able to distinguish themselves, offer a

single intensive semester on campus. With their online and on-

campus coursework combined, they would earn a full master’s

degree.

Bully for them, but the hidden beneficiaries of this setup would

actually be the online-only MicroMasters holders who never set foot

on campus. Precisely because MIT would be treating that initial

salvo of online courses as credit-worthy for the couple dozen

students jumping from the internet to an on-campus master’s

program, it testified to the value of tens, perhaps hundreds, of

thousands of stand-alone MicroMasters’ degrees out in the larger

world. Our online credential would be backed by on-campus gold.

Meanwhile, depending on the specific master’s program we

picked to pilot this new progression, using the MicroMasters as an

on-ramp could substantially broaden the applicant pool for the full

master’s degree. In theory—and this would be the real test of the

entire scheme—infusing a traditional, on-campus master’s program

with the fresh blood of MicroMasters students from different walks

of life, all around the world, might, if anything, improve the quality

of master’s graduates we ultimately released into the wild.

The biggest question was who might be willing to crack their

department’s master’s program open—but this, at least, was an easy

call. I went straight to Yossi Sheffi, who heads MIT’s Center for

Transportation and Logistics. Sheffi’s unit offered a master’s degree

in supply chain management, and I knew him well from my RFID

work, which involved tinkering with industrial supply chains.

Sheffi’s team already couldn’t churn out supply chain professionals

fast enough to meet industry demand, which meant, we reasoned,

that there was a wide world of serious companies that would be all

too happy to recognize a scrappy, new supply chain credential,

assuming the quality of our graduates held up. Sheffi himself,

meanwhile, was the perfect co-conspirator. A serial entrepreneur

who had brought five successful companies into the world, he was

ready to move fast, and as the godfather of a relatively new master’s

degree, he knew the sorts of challenges awaiting us as we floated

the MicroMasters scheme to the larger MIT community.

When I broached the idea, Sheffi became immediately

enthusiastic. “It’s the right idea at the right time,” he later recalled

thinking. He roped in Chris Caplice, the Center’s executive director,

who would design the new credential and teach several of the

courses involved. Sheffi told him, “Chris, we are not stopping. We

are doing it as if it’s a startup. The speed is everything.” There would

be internal pushback, and understandably so: We were talking

about splitting educational atoms—breaking apart what had been

the Institute’s most fundamental unit of education. But Sheffi

declared that “we’re going to do it and then I’ll get MIT to come

around.”

And that’s essentially what happened. The process wasn’t exactly

easy or straightforward, but both the administration and the faculty

gave the idea a fair hearing, and eventually things began to flow

more smoothly. Sheffi, Caplice, and Eva Ponce, a senior logistics

researcher who ended up running the day-to-day operations of the

MicroMasters, took the existing slate of three supply chain MITx

courses and added two more, creating a five-course sequence. And

students who had been taking those initial online supply chain

courses, going back all the way to 2014, found themselves presented

with a shot at a MicroMasters, and possibly even a full master’s on

campus.

Paulina Gisbrecht, a native Muscovite who had spent most of her

early career in Germany working for GE’s thermal services unit, was

one of them. She had minored in logistics at university and found

herself introducing some newfangled logistics principles to her unit

at work, which sometimes ran into problems sourcing spare parts

for massive steam turbines. Shortly after completing a business

school certificate, she began looking for a follow-up course of some

kind. A friend pointed her to MITx, where she discovered a brand-

new slate of supply chain MicroMasters courses. She began to read

about the program and realized the courses could teach her “a lot of

analysis stuff and really quantitative things”—the nitty-gritty of

supply chain dynamics that her relatively cursory undergraduate

coursework hadn’t dealt with. Unlike some other online courses,

however, the new MicroMasters courses were only offered at set

times in the academic year. She checked when the next introductory

course began. It was slated to start on that very day, in just three

hours. “It was like, ‘Thank you, God. You gave me a course today

that I was looking for,’ ” she said. “That was a sign.”

Srideepti Kidambi, Gisbrecht’s eventual classmate, found her

way to the same place via a different path—a surprisingly familiar

one to me, in fact. Hailing originally from India, she earned a

bachelor’s degree in mechanical engineering from BITS Pilani (a

prestigious private technical university), and, after graduating, she

found herself working as a supply chain engineer for Schlumberger,

the selfsame company where I’d found my first job after university.

She even underwent a training period on an oil rig. Afterward, she

bounced around the world for a few years: Pune, in India; to

Houston; to Singapore; where she found her way into the consulting

world. Then she and her husband started a family. “The consulting

life with two kids didn’t really go very well together,” she said, and

she left her job. Around the same time, her husband accepted one in

New York City, and the family moved yet again. Soon enough, she

was ready to return to fast-paced, high-impact work, but found the

prospect of her former travel schedule untenable. She mulled going

back to school, and even looked into a traditional master’s in

business administration, but the timing, and the time commitment,

never felt right. The MicroMasters, however, “was in that sweet spot

for me, where I could actually work and study at the same time, and

didn’t have to travel.”

While starting her first online course, she began interviewing for

jobs. “I was looking for companies that were more in the startup

phase,” she said, where “you could actually drive a lot of change. So

that’s when I started looking at Rent the Runway, Blue Apron,

Shapeways, a couple different companies in different industries.”

The MicroMasters proved “a very good conversation starter” in

the interview process, she said. The chief logistics officer at Rent the

Runway, in particular, was blown away by her progress; it turned

out that he had been attempting the course in his own spare time

and knew how demanding it was. “He didn’t end up finishing it,” she

said, “but he was like, oh my god, I can’t believe you’re actually

going through all those sums, you’re actually doing all the math.”

He ended up hiring her.

The supply chain MicroMasters was, indeed, extremely rigorous

—and demanded a lengthy commitment for anyone planning to go

the distance. Each of the five courses took about three months.

From the start, Kidambi had hoped to fight her way into the blended

on-campus program, but “my family in general was not sure if I

would actually be able to finish the whole thing,” she said. “I was

like, you know what, let me give it a shot. Maybe if I like it, I’ll

continue it.” Instead of adding yet another chore to her already busy

days, however, the courses turned out to be “intellectually very

stimulating for me and very fulfilling.”

Gisbrecht had a similar experience—in the beginning, anyway.

The MicroMasters “is a lot,” she said. Prior to signing up, she had

already booked a vacation to the Philippines, and so her third and

fourth week of the first course found her studying on vacation.

“Everybody was diving and I was sitting in the room,” hard at work,

she said, “but it was worth it. I just didn’t want to miss it. I did the

first fundamentals course and I did well.”

In fact, she aced the first two courses. “Maybe, maybe I will have

a chance,” she thought, of making the cut and joining the blended

cohort on campus. She wrote in her diary that she planned to get at

least 90 percent in her courses. At the time, “I didn’t know that I

could do better than 90 percent,” she said, chuckling.

An ocean away, as Kidambi moved through the same opening

courses, her boss at Rent the Runway gave her the time she needed

to keep up. “He was like, ‘Okay, I know you’ve got a midterm

coming up. It’s okay, take some time off, go do it.’ Because he saw

how intense it was. That really helped me,” she said.

Around the same time she approached the second or third

course, “Rent the Runway started thinking about growth and

expansion,” she said. The company, perhaps unsurprisingly given its

name, rents out designer clothing, and its business model hinges on

its ability to send out, receive, and clean its garments—which calls

for an extremely efficient turnaround. Every one of the fast-growing

company’s garments, however, passed through a single facility in

New Jersey—“the world’s largest dry-cleaning facility,” Kidambi said

—a classic recipe for a logistics bottleneck. A second facility was

clearly overdue. “From the concepts I learned at SC2x”—a highly

analytical supply chain design course—“I actually built a network

strategy model,” she said. She showed it to her boss, who “took it to

a larger audience, the COO, the CFO, and everyone.” In the end, the

company adopted her plan to open a new distribution center in

Arlington, Texas, which would handle 40 percent of the overall flow

of garments.

Kidambi was doing so well at her job that when she expressed

her continued desire to attend the on-campus master’s program, her

colleagues expressed confusion. “People were like, ‘You don’t even

need a master’s. You’re good the way you’re performing,’ ” she said.

But an alumnus of MIT’s traditional master’s program pulled her

aside. “He was like, ‘Forget what everyone else says. Just go do it. I

think you’re going to regret it otherwise.’ ”

What neither Kidambi nor Gisbrecht knew, however, was their

chances of admission. “I had no clue,” said Kidambi. “I didn’t know

whom I was competing against.” Gisbrecht, meanwhile, hit a snag in

the third course in the series. The final exam had “one very tricky

question,” she said, “so, in one course I actually scored not that well.

A ‘B.’ I thought, that’s it. I have no chance.” She wasn’t the only one

stymied by the question, she said. “I know a couple of people who

were so active before,” on the course’s message boards, “and who

just jumped off because they were so destroyed by this.”

That same week, however, she received an email from MIT

asking her to sign up to be a community teaching assistant:

someone who could help other students who were struggling. She

took it as a signal that she still had a chance, and gladly assented.

All told, the entire MicroMasters component of their master’s

degrees took both students sixteen months, including time spent

studying for a single, high-stakes final exam, proctored via webcam.

“One guy,” said Gisbrecht, “was working in Sudan at that point of

time, with literally no connection to internet.” So, rumor had it, he

claimed his company’s entire bandwidth. “He just plugged in and

took all the internet. He was just like okay, tomorrow I’ll have to

deal with it, but now, I have to do my exam.”

“On the first of August, we received our admission,” she said.

“I was like, I’m going. I’m very excited,” said Kidambi. “For a

couple of years, I couldn’t get myself to go to school,” but now, “I

was like, I just want to go and get it done,” she said. “All my hard

work paid off.”

A BETTER WINNOWER

Undeniably, even with the MicroMasters in place, a winnowing is

still occurring in the supply chain master’s program. At the moment

of writing, 300,000 have registered for at least one supply chain

MicroMasters course, 30,000 of whom have earned a lower-level

certificate for completing said stand-alone course, and 1,800 of

whom have earned the larger MicroMasters credential. Of that

1,800, almost 15 percent have applied for the 40-odd spots reserved

in every year’s on-campus master’s cohort for online learners,

known as blended students, who join midway through the

program’s two semesters. The applicants who come in from the

online cohort, however, are such high achievers, said Eva Ponce,

one of the program’s principal administrators, that it’s likely that

students are actually self-winnowing, rather than wasting time on

an unlikely application.

But the bestowal of a high-value MicroMasters on even students

who don’t find their way onto campus means that the year-and-a-

half-long ordeal is anything but a waste of students’ time; so long as

they pass their courses, they get a valuable credential for a fraction

of the cost of a master’s degree: $1,000 total, $1,200 if they choose

to sit for the final exam.

And meanwhile, if this new winnowing process is not perfectly

meritocratic—it still relies on high-stakes tests, for instance, with

their intrinsic drawbacks—it at least comes closer to that ideal than

traditional admissions processes, and leaves less human potential

on the table.

Part of that story has to do with the very deliberate way Chris

Caplice has separated testing-for-promoting-learning from testing-

for-admissions. Initially, when MITx’s supply chain courses did not

lead to on-campus admissions, Caplice treated assessment purely as

a teaching tool. “There was rampant cheating, to be honest,” he said,

but it didn’t much matter. The low-stakes testing, designed to

encourage collaboration, provide instant feedback, and promote the

effortful retrieval of the sort advocated by the Bjorks, was an

important part of what made the courses sound from the standpoint

of students’ cognitive processes. If students cheated, they only

cheated themselves.

When those same courses became part of the MicroMasters,

however, and therefore eligible for MIT credit, “everything changed.

And so that’s when the assessment became really critical,” he said.

An easy mistake would have been to clamp down on the existing

testing regime, making it harder to cheat but diminishing the tests’

instructional value. Instead, Caplice simply added more tests.

Today, the easy-to-cheat, low-stakes tests remain, but so do an

ironclad set of midterms and finals, which, thanks in great part to

randomization techniques developed by the physicist Ike Chuang,

are next to impossible to cheat.

The upshot is that the intrusion of a winnowing function in the

course hasn’t much affected how the online course’s content works

from a cognitive perspective. All told, thanks to such touches as the

continued presence of learning-centered tests, pause-able and

rewindable video, and the fact that the videos are limited to ten

minutes in length, the online instruction remains arguably “a better

method of teaching certain things than face-to-face,” Caplice said.

Tempering the coldness of the ironclad assessments, meanwhile,

is the fact that the people running admissions for the on-campus

master’s degree are the same as those running the MicroMasters. As

a result, it becomes possible, when assessing students, to put a

single bad test outcome or two into a larger perspective. As

Gisbrecht discovered, although a single wrong exam answer dealt a

hard blow to her overall course grade, the admissions team saw fit

to overlook it. “That’s the good point about this online learning,”

she said. “They actually review all of your performance. If you have

maybe one time a bad result, then they say ‘Okay how are you

performing in the entire course? Oh, you’ll perform very well.’ ”

By the time students finish the MicroMasters, “we know them

better than their mother knows them,” said Yossi Sheffi. “We know

everything: how they think, what they do. So we could choose really

the best.”

At the same time, the MicroMasters program casts its net over a

far wider applicant pool than the traditional admissions process,

bringing in a greater variety of so-called traditional and blended

applicants alike. Sheffi leaned in and raised his eyebrows. In the

master’s program, he said, “we have one blended student—we did it

without telling anybody—one who doesn’t have a bachelor’s degree.

He was working and a very smart guy. He did great on the online.

We said, You know what? Let’s take it to MIT, let’s see what

happens.” He laughed. “He was an A student. Aced it.” Now, he said,

the program publicly states that it will accept highly qualified

master’s students even if they don’t hold a bachelor’s degree.

The program’s proof, ultimately, is in the blended students’

performance on campus. In yet another independent study, Justin

Reich and his coauthor compared their performance against

traditionally admitted master’s students in the supply chain

program. Not only did the blended students outperform the

traditional students in supply chain courses, but, in courses they

took outside the supply chain program, they also outperformed the

larger population of MIT students. The findings are a testament to

the sheer human potential sitting latent, just outside the traditional

sight lines of the academy.

—

Today, the supply chain MicroMasters won’t only get you into MIT.

Although in my biased opinion our master’s program remains the

top prize, twenty-one other universities on five continents will also

give you credit for the online coursework. The supply chain

program, meanwhile, was also just the first of many. As of mid-

2019, there are fifty-two MicroMasters programs on offer at

universities all around the world, four of which are provided by

MIT.

Perhaps most importantly, the MicroMasters saga has allowed

us to take a highly intentional look at what exactly makes a higher-

ed degree valuable—and what aspects of traditional higher

education run at right angles to students’ goals, or even against

them.

There is a truism whispered among administrators at top

colleges and universities concerning why students keep signing up

for elite schools. The value, the thinking goes, comes in three parts:

the stuff you learn, the people you meet, and the fact that you got

in. Add in a few more elements of campus life—athletics, say, and

parties, and ivy-covered buildings—and you’ve got a stereotypical

sketch of what many American universities offer undergraduates

and master’s students.

The MicroMasters, meanwhile, prioritizes the “stuff you learn”

above all else. It also preserves the “who you meet” as an important,

if secondary, concern. (Indeed, at the first-ever MicroMasters

Completion Celebration, suspended across a gigantic

videoconference in May 2017, small groups of students in cities all

around the world called in from house parties, filled with people

they’d met online.) It obviously strips away the physical

infrastructure of the university, and some of how university life is

organized temporally. But what the MicroMasters truly explodes—

deliberately, intentionally, pragmatically—is the “fact you got in.” In

fact, it reveals that “the fact that you got in” was never a unitary

element of higher education. It was always two things framed in

opposition to one another: a testament to the promise of the

admitted student, and the implication that everyone else denied

admission is less promising. The MicroMasters dispenses with this

Manichaean mode of thinking. In fact, it’s possible to be promising

in an absolute sense, relative only to the rigors of the coursework

standing before you, irrespective of the promise of your peers. The

core project of the MicroMasters, then, is a repudiation of the

perspective we inherited from the first intelligence tests, which

normalized one’s score against those of one’s contemporaries. In

the MicroMasters, if you prove equal to the material, you get a

certification—no matter how many of “you” there are.

Exclusivity, meanwhile, does persist in the MicroMasters-fed,

on-campus master’s programs—but no longer as a feature of higher

education so much as an unfortunate bug: a side effect of the fact

that any face-to-face education program must necessarily be limited

in scale. The second half of the MIT supply chain master’s

sequence, for instance, features a student thesis and a lot of

collaboration on the sorts of problems that don’t have definite

answers, the sort of work that’s especially hard to translate to a

digital-only medium. As Erdin Beshimov, who oversaw the initial

launch of the larger MicroMasters credential, likes to say, we’ve

taken MIT’s Mens et Manus credo and put the Mens online, while

keeping the Manus on campus.

There are drawbacks to this arrangement: to delivering a

corpus’s hard facts first, and pursuing complex problem solving

second. It’s harder to use complexity to trigger curiosity, to motivate

learners, and to contextualize knowledge; as outside-in-leaning

educators like Mitch Resnick and schools like Ad Astra would

prefer. However, at least for adult students doing master’s-level

work, I think the benefits outweigh the costs. By putting a given

field of study’s hard knowledge online first, we can teach it to a

sizable chunk of the world who might otherwise never get the

opportunity.

But why bother, you might reasonably wonder, to keep Manus in

the equation at all? If Manus is difficult to scale online and

expensive to run in person, and given that researchers are not even

in agreement about whether problem solving can be taught as a

stand-alone virtue, perhaps we should just cut our losses and stick

to teaching hard facts and skills over a broadband connection.

My answer is a simple one: If the ultimate point of education is

to create learners who can change their world, then Manus is non-

negotiable—and access to it must be made more democratic.

Whether it takes the form of solving problems on an oil platform

(or, more preferably these days, a wind farm), or perhaps piecing

together the argument for an essay about poststructuralism in

literature, or coming up with a treatment plan for a hospital patient,

or designing and building a robot, doing—designing—remains the

linchpin of an activated education. For the mind to fully, truly grasp

something, then the hand must grasp as well—although perhaps not

for the reasons one might think.

—

To stick to the world of mechanical engineering, for an example of

someone saved by the power of hands-on, complex problem solving,

one need look no further than Woodie Flowers himself. Outlandish

machinery was a constant in Flowers’s life starting at a young age.

During his youth in rural Louisiana, local sawmills produced literal

tons of waste wood, much of which took the form of giant, live-edge

slabs. At most sawmills, two unlucky fellows would have the

dubious pleasure of hauling those slabs over to a burning woodpile

and chucking them in. “Hot as hell, insufferable job,” Flowers said.

So his father, a welder, “took a piece of 30-inch-diameter pipe,

welded teeth on the outside, spun it at 2,000 RPMs, so it looked like

the most evil thing you’ve ever imagined.” He would drop the slabs

onto the spinning, toothed cylinder and shoot them off into the

distant fire. “Bang!” he said. “You could throw it a hundred yards, no

problem.” His father’s aim was so accurate, “Dad could almost stack

stuff with the thing.”

In high school, Flowers tried to pick up a date in an army vehicle

with wheels in front and tank-style treads in the rear. “I was so

happy I was going to be able to pull into the local Dairy Queen in a

half-track,” he said, but his date refused to get in. His crowning

glory was his hotrod roadster, which he built out of found materials.

“I didn’t have any money, so everything was pretty crude, but it was

really fast-accelerating,” he said. “I got a ticket one time for no

headlights, no taillights, no proper exhaust, a whole list of stuff. No

fenders.” He chuckled. “I survived.”

Despite his budding engineering chops, the young Flowers had

no plans to attend college. In his final high school semester,

however, a social studies teacher who knew about his interests

pulled him aside. He’d noticed that Flowers couldn’t fully extend his

left arm, the result of a fall out of a tree in the second grade that had

fractured it in multiple places. The teacher said, “Boy, we got to get

you declared a cripple.” An orthopedic surgeon from the nearest

hospital made Flowers’s disability status official, which equated to a

rare opportunity: a college scholarship. “I gave up on getting a job in

the oil field and buying a good Corvette,” he said. His path took him

instead to Northwestern State University at Natchitoches,

Louisiana, then Louisiana Tech, then MIT.

When Flowers spun an abbreviated version of this tale at the

2.007 competition opening ceremonies, it sounded familiar to one

student in particular: Richard, the dark-horse contender, whose

robot had sent concern into the heart of even the unflappable

favorite, Tom Frejowski. Richard was a couple of years older than

his classmates, which created some distance in terms of

temperament. In the lab, while others clustered in groups of two or

three, he could often be found working alone, a quiet smile on his

face. Still, the first time his robot had fired up its thruster spinner, a

crowd immediately gathered, drawn by its Harley-Davidson growl.

If his motor was the only one of its kind in the class, so too was

Richard. He’d spent the first part of his childhood in a suburb in

southwestern Virginia, where his father worked as a biology and

biochemistry college professor. Then, when Richard was fourteen,

the family made a change. They moved an hour north, to live and

work on a farm. And Richard’s homeschool education, which had

been at least somewhat structured up to that point, became

decidedly less so. The family had moved in the summertime, and

that season, Richard began farming in earnest: beef cattle, organic

vegetables, organic seed crops. Then in the fall, when it would

normally have been time to start a new school year, “It just never

really happened, because we were very busy,” he said. “My parents,

they just basically told me, ‘This is a really good educational

opportunity. You’ll probably learn more here doing this than you

would doing schoolwork right now.’ ”

One of the things he learned about was farm equipment. He

found himself responsible for fixing tractors, cars, and ATVs. Along

the way, he gained a general sense of where and how machines fail.

He also built farm equipment from scratch. Funnily enough, the

homemade machine he was proudest of—his equivalent of

Flowers’s hotrod—was a device that blew air through a column of

seeds to remove shells and stalks and rocks. “I built a winnower,” he

said—but sorting the seed from the chaff proved harder than he’d

expected. “I was trying to figure out how to make a bunch of

different gates that I could open and close to adjust things,” he said,

“and it just didn’t really work. I wasn’t able to get the control I

wanted to.” Ultimately, he jerry-rigged things until it functioned—a

fantastic achievement for a young, untrained engineer—but only

inefficiently, and without granting Richard any degree of fine

control over the seeds he was cleaning.

Eventually, he realized he wanted a more formal engineering

education. Now eighteen years old, he decided to forgo a high school

degree and instead studied enough on his own to qualify for an

associate’s program at a local community college. From there, he

applied as a first-year to MIT.

Flowers, upon learning about Richard’s background, speculated

that MIT’s director of admissions, a Course 2.007 alum, might have

had something to do with his presence. Whoever made the call to

admit him, it was the right one. Richard’s robot had turned the

heads not just of the other students but also of his professors.

“The VS-11”—a small electric motor provided to all 2.007

students—“is a powerful motor, and he took some gears out of it,”

explained Amos Winter. “I don’t think we’ve ever seen that.”

Of all the motors available to 2.007 students, the VS-11 was

capable of producing the most torque, but most students had

avoided using it for thruster-spinning purposes because it was a

servomotor, designed to move slowly to a set position, and not

beyond 180 degrees of rotation. Modifying it to turn continuously

was relatively easy—“a hack everybody does,” Winter said—but even

then, though quite torque-y, it would turn only phlegmatically.

What Richard realized, however, was that the VS-11 only appears

to turn slowly on the outside. The actual motor, hidden inside the

VS-11’s plastic casing, spins in a blur. Between that inner motor and

the outside world is a series of gears that transform the inner

motor’s frantic speed into measured, implacable torque. “Yeah, the

gear ratio on those is, like—I don’t know—200 or 400 to 1 or

something. It’s enormous,” Winter said.

What students normally do, if they want to use the VS-11 to turn

a wheel quickly, is build an external gearbox to translate its torque

back into speed, which inevitably introduces friction and effectively

robs the VS-11 of much of its power. Richard, instead, cracked open

the motor’s casing. “What he did is he took out some gears, so then

it was probably like 10 to 1,” Winter said, “and he had very few gear

stages and, I think, very good bearings, so it didn’t lose a lot of

torque from friction.” The hack required not just a watchmaker’s

touch but also the replacement of the motor’s circuit board with one

Richard had home-cooked for the job.

Winter shook his head in admiration. “That dude is brilliant.”

TEACHING PROBLEM SOLVING

By the first match of the day, it was clear that Course 2.007’s

students had learned plenty of things. At the start of the semester,

Amy Fang had come in with a decent theoretical grounding in how

gears affected the torque output of a motor, for instance, but she

didn’t know how to fit gears together to form a transmission. By the

end of the class, she’d won an award for the transmission she’d

built, which transferred the power of not one but three motors to

the X-wing’s thruster.

A harder question was whether students had improved their

ability to solve complex problems, a trait that some educators

consider unimprovable. Brandon, after aborting his first plan, had

thrown together a serviceable, thruster-spinning robot in the space

of a handful of weeks. Then he did it again: He built a second robot

for his wingman Josh to pilot, this time in a matter of days. This

auxiliary robot, though legal according to the rules of the contest,

had to be built with a dramatically different control scheme,

governed by an Xbox videogame controller rather than a model

airplane remote, which posed an entirely new engineering

challenge. Nevertheless, his turnaround time was remarkably short.

Somewhere along the line, he had clearly attained some hard-to-

pinpoint knowledge about engineering and design.

What was the identity of that knowledge, exactly? Fascinatingly,

both Sanjoy Mahajan and Mitch Resnick—representing inside-out

and outside-in educational traditions, respectively—laid claim to

aspects of the learning being done in Course 2.007.

Resnick’s outside-in claim made the most intuitive sense. By

literally building things, students caused their schematic trees to

grow markedly fuller: flowering oaks where there had once been

mere saplings. “As soon as I start creating, that gives me new ideas,”

Resnick said. For instance, when a student learns to use, say, the

automatic lathe workstation in the Pappalardo Laboratory to

fabricate a grooved shaft of some sort, other possibilities posed by

the lathe begin to unfold, and soon that same student finds herself

using it to create, say, flanged bushings to add rigidity to the joints

of her scissor lift. If merely learning to use a machine complicates

one’s reality, learning to build one does so on a whole higher order

of magnitude. For instance, everyone graduates from Course 2.007

able to invent robotic solutions to everyday annoyances like

household chores. Their immediate surroundings become solvable.

The world, in a small way, becomes changeable.

But still, the question of whether the course improves deep-

seated problem-solving skills, or merely adds to the highly

organized, interconnected branches of data housed in students’

long-term memory, remains open. After all, knowledge of what a

lathe does is just that: raw knowledge. In fact, a good deal of Course

2.007 consisted of the direct instruction of principles—often

delivered through the media of online tutors and videos. And, as

Mahajan pointed out, although there was plenty of discovery-style

learning going on in 2.007 at a surface level, a closer look revealed

the course to be highly scaffolded: organized to break leaps of

discovery into more manageable steps. Students like Brandon and

Amy Fang and Z may have felt like they were chucked into the deep

end of the learning pool and abandoned to sink or swim, but in

point of fact, the course strategically placed a sequence of life

preservers within reach. These included the course’s series of

“physical homeworks,” which forced students to achieve certain

engineering milestones before starting in on their competition bots.

“They’re not thrown in. They’re not just told, ‘Okay, here, go figure

out how to build a robot and try experiments,’ ” said Mahajan.

“They’re taught theory. They’re taught how to work together. And so

that’s not discovery learning at all.”

—

To mark the official start of competition, the Chorollaries, an MIT a

cappella group, sang the National Anthem, which was greeted with

hearty applause. Then, blasting forth from loudspeakers, came

another anthem chosen to lift the heart of every geek in attendance:

John Williams’s Star Wars theme. The stage set, Winter and his co-

lead, Sangbae Kim, burst through the curtains clad, respectively, in

startlingly realistic Darth Vader and Chewbacca costumes. The

crowd erupted.

The opening match was Richard’s first contest of the night. His

robot, named Tornado, trundled autonomously up to the lower

thruster and spun it at high speed, emitting its characteristic growl.

It worked by means of a friction drive: turning a small wheel against

the face of the thruster, like a tiny unicyclist riding on a record

turntable—a design strategy that, of the final thirty-two competitors,

only Richard and Amy Fang had attempted. Then it did what Tom’s

robot couldn’t. Now under Richard’s manual control, it flew up the

elevator, repeated its feat on the upper thruster, and, to put a cherry

on top, slammed a button that caused the music from Star Wars’

Mos Eisley Cantina to play, which added another smattering of

points to his total. By the end of the round, 937.5 points glowed on

the scoreboard, the competition’s highest score yet. His opponent

never had a chance.

The rest of the first round of competition proved as ruthless a

winnower as any Richard—or E. L. Thorndike—had ever designed.

For the most part, a wide variety of lovingly crafted robots fell

before an onslaught of dedicated thruster-spinners—clearly, this

year’s winning strategy. Brandon and his roommate, Josh, each had

a pair of these spinner bots, and each served as the other’s co-pilot

in the competition. Their first team-up—Brandon’s round, with Josh

assisting—proved sweat-inducing, with the robot under Josh’s

control never quite aligning with the lower thruster. Brandon,

however, pulled out a win with mere seconds remaining by climbing

the elevator and spinning the upper thruster. “That’s gonna be

awkward when they get home tonight,” Winter deadpanned over the

loudspeaker.

In their second team-up—technically Josh’s match this time—

the duo made hasty work of Amy Fang and her beloved Dodocopter.

While approaching the lower thruster, Dodocopter somehow put

one wheel in the trench running down the middle of the game

board, beneath the X-wing’s fuselage. Amy tried to spin the thruster

before the inevitable took place, but to no avail: The robot teetered

and fell. The Dodocopter was extinct, and Winter was sad to see it

go. “Amy did some killer analysis,” he told the audience. “I love her

design.”

That same central trench would swallow Josh’s chances as well,

in the sweet sixteen. By working together on both of their bids,

Brandon and Josh had essentially given themselves two shots at

competition glory. Now they were down to just one—Brandon’s bid

—and the odds seemed not in his favor. His round-of-16 match was

against James Li, who, like Brandon, had a partner to help him drive

his two robots, named Bonnie and Clyde. The bigger of the two,

Bonnie—“Just like the praying mantis, the female is larger,” intoned

Winter—extended a telescoping tower up to the front of the top

thruster. Brandon raced up the elevator and spun his top thruster to

its maximum speed of 25 radians per second. Li’s Bonnie,

meanwhile, fighting some sort of alignment problem, achieved only

a fraction of that.

Still, a fraction could go a long way, because by now the smaller

Clyde, too, had reached the upper deck and inserted a hook behind

the dangling, weighted base of the lightsaber situated in the center,

right above the X-wing’s cockpit. The lightsaber’s heavy handle

acted like a pendulum, and any competitor who pulled it far enough

could multiply her point total by as much as three. Brandon, eyes

agleam, began to ram his robot into Clyde. It was the night’s first

instance of sabotage, which was permitted only for robots that had

reached the upper deck, where the two combatants were now

entangled. “Wow, that is a Dark Side move!” said Winter. Still,

despite Brandon’s worst efforts, the lightsaber continued to tip,

reaching 45 degrees. It looked for a moment like the match could go

to anyone—except for the fact that Josh had quietly been working in

the background, spinning the lower thruster. Ultimately, it wasn’t

Brandon’s sabotage so much as Josh’s quiet success that carried the

duo to the round of eight.

Z, meanwhile, who had worked sabotage into his plan weeks ago,

found himself dreaming up new schemes for each opponent. His

larger robot could spin both thrusters from the front, like several

others, by extending its thruster-spinning fork up on an accordion-

style platform. But his most cunning stroke of genius was the

realization that this rising platform could also serve as his own

personal elevator, capable of depositing a smaller, sabotage-ready

bot on the upper deck right at the start of the round, which could

permit all manner of mischief.

Looking at his tournament bracket, he saw that he would first

run into trouble in the form of Patrick Shin, whose robot could spin

both thrusters from the front. “Honestly, I may have my second

driver drop down to block him,” he said—a maneuver that Z referred

to as “going ‘Fast and Furious.’ ” It would be technically legal, so

long as it didn’t endanger any nearby humans.

Even Alex Hattori, the student who had competed on the

television program Battlebots, sounded concerned. “I’m glad I’m in

the other bracket,” he said.

In practice, however, the transfer of the smaller robot from Z’s

homemade elevator to the X-wing’s upper surfaces proved trickier

than he had anticipated, necessitating a hastily constructed

gangplank. In his first two rounds, the small sabotage bot fell from

this bridge both times, useless. The second time around, the crowd,

which now understood Z’s strategy, groaned at the sight of the robot

plummeting; they’d wanted to see it do its dirty work. Still, by the

end of the second match, the crowd was chanting “Z.” He had made

it to the quarterfinals. “I never thought I would be in the eight,” he

said, eyes bulging. He embraced his co-pilot, Gabriel, and then both

raced away to tinker with their robots. In fact, he’d make it even

further, winning the next round handily against a bot that oscillated

free of the top thruster at precisely the wrong moment. Z would

move on to the semifinals, where Richard waited with his Tornado

of doom.

Brandon, meanwhile, was up against Alex Hattori of BattleBots

fame, whose twin robots were theoretically capable of racking up

astronomical sums. Instead, however, the match unfolded in a

cavalcade of errors on both sides—including a moment when

Brandon’s robot fell on top of the one piloted by Josh—eliciting

frustrated moans from the crowd. It looked like a tie was in the

making, in which event the lighter pair of robots would advance. But

Josh and Brandon had one advantage Alex lacked: they had read the

fine print in the rulebook, which permitted them to lay down a

single stormtrooper on their side of the game board at the beginning

of the round. If pushed into the central trench, it could earn them a

measly five points—essentially a concession built into the

competition for students with the simplest robots, all of whom had

been eliminated yesterday. Now, with about ten seconds left, that

loophole was their only hope. Josh’s robot was still upright, but it

wasn’t really built for the job, and the moment it drove up against

the heavy, metal action figure, it seemed to stall. “Five,” Winter

announced. The stormtrooper started to slide, and the crowd,

watching the action on jumbo screens, began to murmur. “Four.”

Josh pushed the throttle all the way up. With three seconds left on

the clock, his robot plummeted into the trench, dragging the

stormtrooper with it. Brandon’s team had won by five points. And

suddenly, the audience, which had been cheering throughout the

night in a good-natured yet contained sort of way, lost its collective

mind. Many had come merely to support their classmates out of

friendly obligation, but now it was becoming clear that they were

watching the best sporting event of the year.

—

Part of why the crowd in Johnson Rink reacted so passionately to

Brandon and Z was that they had begun to exude the sort of

confidence that one loves to see in professional competitors. There

was a moment in the quarterfinals when, with the clock still

running, Z turned and high-fived his partner, which called to mind

the sprinter Usain Bolt’s tendency to glance back at his cloud of

dusty competitors in the 100-meter dash. The self-assurance Z

displayed was perhaps a little cocky, but it was also captivating to

witness in someone who had only recently achieved a degree of

proficiency.

Woodie Flowers later alluded to this feeling when he described

what was to him the secret purpose of the hands-on, Manus part of

an MIT education. Education is what happens when you learn “to

think using calculus,” he reiterated—but that’s actually a two-part

proposition. The first part is outward-facing: You have to

understand how calculus relates to the world around you at a deep

level, so that calculus becomes a tool applicable to a wide variety of

situations. It must be broadly contextualized and also, in the

wording favored by Sanjoy Mahajan, “overlearned,” so you can

reference it on the go, without clogging up your working memory.

The second, inward-facing part is less intuitive but just as

important. Education means gaining a second-nature understanding

of how you, as a potential agent of change, might use your

knowledge and skills to affect the world. “I believe that true

education is about a process that allows one to develop rational self-

esteem,” Flowers said. That is, for anyone hoping to affect the

world, prodigious knowledge and skills are never enough; you must

also prove to yourself your mastery of that knowledge, of those

skills, in order to understand their wider relevance.

“I used to go to conferences,” talk about 2.007, and then “get

really frustrated,” Flowers said. “A faculty member from another

school would come up and say, ‘Yeah, we do creative exercises. I had

this consulting job, and I had a problem that I had no idea how to

solve, so I gave it to the students as a creative exercise.’ And you just

want to deck them. That’s the dumbest goddamn thing you can ever

imagine doing. I mean, why would you take somebody’s creative ego

and trash it from the beginning?”

Nurturing a creative ego, rather, is where the Manus aspect of

education excels. At the beginning of the semester, Winter had

introduced the design process he and the other 2.007 lecturers

would propound throughout the course. “Design doesn’t work like,

‘you have a great idea, you make a Saturn V rocket, and you go to

the Moon,’ ” Winter had said. “Try to picture a Saturn V rocket in

your head. Not just the shape, but, like, one of the O-rings in one of

the thrusters in the bottom.” The rocket was sixty feet taller than

the Statue of Liberty, filled end to end with complex machinery and

electronics. “It’s massive, massive, massively complicated. And so

people just don’t have the cognitive ability to carry all of these

details in their head. They have to break it down to smaller, more

tractable parts.”

He loaded a slide of a diagram that was originally created by the

product designer Damien Newman. A black squiggle on a white

background, it looked like someone’s chaotic pen-and-ink signature,

except that from left to right its frenzied loops hewed toward some

invisible central axis, until eventually a single flat horizontal line

emerged. “It basically starts out with research and

conceptualization,” Winter said, gesturing to the squiggliest,

leftmost part of the diagram, whose multifarious loops represented

the many routes that might lead to a complex problem’s solution.

Research and hard thinking eliminate a number of these

possibilities. Next, he gestured at the slightly more orderly middle

section of the diagram. “You evaluate your ideas, you narrow ’em

down, you get more refined, and eventually”—now pointing to the

spot on the diagram where the several remaining lines coalesced

into one—“boop, you come up with a final design.”

When first approaching a complex design problem, “you can

believe six impossible things before breakfast. Near the end, you’re

making an absolute prediction about what the universe will do,”

said Flowers. “I know really good designers who are comfortable

everywhere in the space, and they never get confused about where

they are,” he said. “To me, elegant design is people that run back

and forth”—to different parts of the design squiggle—“with fluidity

and precision.”

Fluidity and precision: If that sounds like the sort of thing that

draws spectators to sporting events, it should. And indeed, if you

managed to chemically isolate what the crowd in Johnson Rink was

applauding when they stood up and stamped their feet for Brandon

and chanted Z’s name, it would have been exactly that: the precision

on display in their robots and the fluidity apparent in their ability to

wield them.

In the fluidity and precision of the Course 2.007 competitors,

too, I see the greatest argument for further disentangling the taken-

for-granted aspects of our inherited educational structures. In

2.007’s pocket universe, not only are students freed from fear, but

intractable points of pedagogical disagreement, such as the

teachability of problem solving, begin to feel less pressing. Unlike

“problem-solving skills,” which Z and Brandon might or might not

have had in spades from birth, their self-confidence as roboticists

was something they had certainly gained as a result of 2.007’s

deliberate, highly scaffolded approach to hands-on instruction. Once

you accept that nurturing students’ creative ego is essential, then

ancient, Jesuitical disagreements about problem solving simply

begin to lose their urgency. Regardless of whether such skills can be

taught, you’re going to have to use hands-on, scaffolded, discovery-

style pedagogical tactics for the development of a creative ego

anyway. Only the Manus part of Mens et Manus can foster the

sense of self-confidence you need to survive the ups and downs of

the design squiggle: a sense of self that will keep you anchored

whether you’re designing a government policy, a piece of writing, a

robot, or a symphony.

—

Or even if you’re designing new educational standards. Looking

back, without precisely such a sense of creative ego, I could never

have even conceived of a viable pathway for the MicroMasters. The

creation of new standards in any complex field is a bit like building

a rocket, at least in the sense that there are far too many pieces (and

interested parties) to ever account for all at once. When we set out

to establish a new RFID standard for the world’s supply chains, I

lucked into a winning formula (and team of collaborators) for

aligning all the moving parts. One consequence of that experience

was that, when it came time to plan out the MicroMasters, I knew it

could be done. I understood what the points of uncertainty would be

like and what it would feel like to overcome them. And I also knew

that if we found a way to somehow attach value to the standard, we

could make it stick. And that’s precisely what we did: We thought

very intentionally about what makes educational credentials

valuable to their owners, and we created a version that married

maximal value with minimal exclusivity.

That’s a formula we’ll hold on to moving forward. Ultimately, if

existing institutional structures continue to stand in the way of

widely available, cognitively user-friendly learning, then perhaps

tomorrow’s learners will need to hitch themselves to a new kind of

rocket. As we’ve seen, a whole host of organizations are

experimenting with ambitious new schemes for how students might

move through curricula. At MIT in particular, there are enough of

these now up and running or in the works that, when put together,

they begin to look almost like a coherent, alternative pathway for

advanced learning.

And indeed, like a Saturn V rocket, there are lots of separate

parts to keep track of. Here are the most critical modules. Perhaps

the most mature element in this alternative pathway is our ever-

growing complement of free (or nearly free) online courses, which,

as we’ve seen in the MicroMasters, can be used not just to teach,

but also as admissions criteria for further levels of instruction. Such

further instruction, meanwhile, might include not just master’s

degrees, but also intensive midcareer bootcamps, which are now

running continuously at MIT. These cram an entire semester-long

course’s worth of hands-on learning into a single week—admittedly

suboptimal from a spacing perspective, but necessary for our

bootcamps to fit into the packed schedules of the attendees. (You

can often tell where a bootcamp is taking place by the piles of

exhausted thirty-somethings catnapping on the lawn.) For the level

beyond that, we’re setting up a system of one-on-one

apprenticeships, not with professors as advisors so much as

“entrepreneurs, investors, corporate executives,” explained Erdin

Beshimov, who is leading the program.

Just these three ingredients might themselves be enough to

create a viable, nontraditional route to intellectual superpowers in a

given field. First, online learning would deliver hard knowledge and

skills, then hands-on bootcamps would contextualize that

knowledge while nurturing a healthy creative ego, and finally an

apprenticeship would offer the chance to turn around and apply that

knowledge directly to a field’s emerging problems.

This potential progression would necessarily exist apart from

graduate education as we know it, and be undergone mainly by

people for whom traditional advanced degrees aren’t quite the right

fit. But there’s no reason that traditional degree programs, too,

shouldn’t be armed with some of the same sorts of instructional

ingredients. At the college level, blended or flipped learning is one

obvious, cognitively user-friendly approach that fits easily into

traditional educational infrastructure. (In fact, as my colleagues

remind me when I get too overexcited about these things,

humanities professors have always run flipped classrooms, simply

by asking their students to “please do the reading before class.”)

One less obvious opportunity raised by such a setup, however, is

that the online part of a flipped course need not be home-cooked at

the same college where it’s being taught. To encourage other

colleges and universities to incorporate our online materials into

their flipped courses, the physicist Krishna Rajagopal, MIT’s Dean

for Digital Learning, has launched a program called the xMinor. The

general idea is that if you’re a student at perhaps a small liberal arts

or community college and you want to take a course that’s not

offered—say, quantum computing—you could take that course

remotely from MIT (or whoever was offering it). You would still

have a local professor, however, who would make those online

materials relevant to your larger education at your college—that is,

who would provide the manus to the online component’s mens.

“The role of the educator is just as central as it was before,”

explained Rajagopal. In this sort of blended course, “the educator is

doing the blending.”

In order to combine all of these loosely connected efforts into

something coherent, I’ve been giving particular thought to the one

educational standard that could rule them all: a modular,

distributed transcript, owned by students, not their educational

institutions. A universally recognized network of unfakeable

transcript entries, not too different from the generalized network

used to track the billions of different RFID tags swirling around the

world, would permit a far more free-flowing experience for

students, enabling them to sample from multiple institutions of

higher education, to mix and match on-campus with online courses,

and to earn traditional degrees as well as newfangled credentials as

needed. Such a system need not be limited to the stuff of transcripts

as we know them—namely, numerical grades. They could also

include portfolios of projects, granting admissions offices a fuller

view of their applicants than is currently possible.

We’re still in the early days of imagining such a system, with a

long line of obstacles both known and unknown in front of us. Our

experience with the MicroMasters has proved, however, that the

creation of new educational standards is far from impossible. We’re

like 2.007’s freshly minted roboticists: surrounded by a world of

problems that once seemed out of reach, but now appear solvable.

Even if my wildest fantasies of success come to pass, however,

and far more knowledge soon becomes far more accessible to far

more people, there will still always be schools that traffic in

exclusivity, conferring name-brand value on attendees via the coins

of “who you meet” and “the fact you got in.” But crucially, top-notch

learning will no longer be locked behind such doors. Increasingly, in

the years to come, the “stuff you learn” will be available to everyone.

THE SHOWDOWN

The Course 2.007 semifinals pitted the upstarts from Winter’s lab

section against the overall favorites: Z versus Richard, Brandon

versus Tom. For once, the outcomes of matches involving Richard

and Tom seemed not to be foregone conclusions, once you factored

in both Z’s and Brandon’s now-apparent lust for sabotage. Z

immediately fell victim to mechanical failure, however, and

although Brandon managed to drop his robot from the X-wing’s

fuselage onto Tom’s, he struck only a glancing blow—too little, too

late.

In the final showdown between Richard and Tom, Black

Sabbath’s “Iron Man” was blasting throughout the arena. Tom

crouched down, eyeballing his robot’s trajectory. The winner was

clear mere seconds into the match, when Richard’s Tornado struck

its target slightly left of center. Its thruster-spinning wheel began to

turn, but the thruster remained immobile, and Tornado slid off to

the side, losing contact. And that was it: Richard would score no

points in the autonomous period, and although he quickly assumed

manual control and earned points on both thrusters, he couldn’t

overcome Tom’s lead. Tom, the favorite from the start, carried the

night, and Winter and Sangbae Kim carried him: on their shoulders,

back and forth in front of the crowd.

But there was one other match that took place before the night

ended—one that proved more of a crowd-pleaser than even the

finals. It was the consolation match between the remaining

semifinalists, and, in effect, the final competition for champion of

Winter’s lab section. Both Brandon and Z were prepared to do

whatever was necessary to win.

By the end of the autonomous period, Z’s double robots had

pulled up to the starfighter’s fuselage and waited at the ready. The

manual control period began, and Brandon raced up to the elevator.

Z’s gangplank unfolded and now Z’s second robot, controlled by

Gabriel, rolled onto the top of the X-wing, beating Brandon to the

upper deck. Z’s personal elevator had finally functioned as intended

and the audience, witnessing this long-anticipated moment, came to

life. The decibel level only increased when Brandon too arrived on

the top deck. Gabriel zipped over to prevent him from coupling with

the top thruster. There was a moment of confusion; the action

became hard to follow, and then the top thruster began to spin.

Strangled yells could be heard from the audience, and then a video

feed showed what was happening: Gabriel was trying to dislodge

Brandon from the top thruster while Brandon, locked in, was

driving his wheels with the full might of his electric motor. The

thruster reached its maximum speed of rotation: points to Brandon.

But then it looked like the tables might turn just as rapidly. Josh

had spun the lower thruster on Brandon’s side to maximum speed,

as had Z to the top thruster on his side. Now all that remained was

for Z to shrink his scissor lift down and spin the bottom thruster. If

Brandon could somehow stop that, the match would be his.

Gabriel’s robot was still in his way on the upper deck, but he was no

match for Brandon as a driver, and Brandon skirted around him and

drove out alone on the fuselage of the X-wing. The spectators,

sensing what was about to happen, literally rose to their feet. Z

plugged into the lower thruster and began spinning it—how fast, no

one knew—while Brandon teetered above him. Then, with a

resounding crash, Brandon landed on the flat top of Z’s scissor-lift

robot and collapsed it to the ground. When the dust settled, the

scoreboard registered an improbable tie: 312.5 to 312.5.

And so out came lab instructor Danny Braunstein, solemnly

hooded in a brown Jedi robe, with a set of homemade scales.

Brandon placed both of his robots on one side; Z placed his on the

other. For a long moment, the scales remained locked, level. Then

Braunstein pulled a lever, freeing them with an audible click. One

set of robots fell toward the floor and the other set rose in triumph,

held aloft like the hand of a victorious prizefighter.

It belonged to Brandon.

In the immortal words of Darth Vader, the learner was now the

master.

\* Many millions of children and teens routinely interact with MIT more indirectly, however,

through such intermediaries as Scratch, Khan Academy, Quizlet, MIT App Inventor,

littlebits, and Guitar Hero: all invented either in-house, by alumni, or even by highly

successful dropouts!

Epilogue

In 2019, two years after he’d delivered his address to Brandon and

the rest of the Course 2.007 students, Woodie Flowers died

following surgical complications. He was seventy-five. The news

came as a blow to MIT, and to a far wider community of learners as

well. In addition to the alumni of his now-famous MIT course,

Flowers also reached millions through FIRST Robotics, the globe-

spanning organization he helped found, which brought robotics

competitions to students in dozens of countries. Factor in the three

years he spent as host of the PBS television show Scientific

American Frontiers, and the vast number of high school and college

courses built on 2.007’s model, and it’s no exaggeration to say that

he contributed to the education of a respectable chunk of the

world’s population. Already, his influence is of the same order as

that of some of the most important names in the educational

pantheon.

Two hundred years earlier, the sound of cannon fire heralded the

end of the legacies of two members of that pantheon: Andrew Bell

and Joseph Lancaster. In 1817, while Lancaster’s schools were still

popping up like mushrooms in the young United States, DeWitt

Clinton, New York’s governor and Lancaster’s most prominent

proponent, announced the start of construction on the Erie Canal.

The ambitious waterway would connect the Great Lakes to the

Atlantic via the Hudson River and its muddy tributary, the Mohawk.

“Clinton’s folly,” as the 363-mile project was known, was originally

derided as the impossible scheme of a grandiose politician, but it

was finished under budget in the span of eight years. In 1825, the

State of New York announced its completion with a sequential

cannonade running the length of the waterway, starting on the

shore of Lake Erie and finishing in New York City. The gunfire took

an hour and a half to travel from lake to shining sea.

The canal was eminently worthy of celebration: It cut

transportation costs of goods by 95 percent and turned New York

City into the primary point of commerce for not just the

northeastern United States, but also the upper Midwest and parts of

southern Canada. It also utterly upended life within its reach. Prior

to the Erie Canal, farmers and artisans had only their neighbors to

compete with. But once that cannonade fired, there was something

new to consider: the national price of beets, of boots, of barrels of

whiskey. “Every wheat farmer was suddenly competing with every

other wheat farmer across New York State and beyond,” writes the

education historian David Labaree in his book Someone Has to Fail.

In a few short years, a host of small, local businesses, especially

family workshops, became economically unviable, no longer able to

compete on price with mass-produced goods from faraway cities. As

canals, turnpikes, and railroads spread, once-reliable ladders to

middle-class prosperity disappeared, and so did much of the social

glue that had held agrarian communities together. The public

responded in part by embracing mass education: expanding its

purview from Lancaster’s needy cases to just about everyone. In the

process, its framers set up educational norms that remain with us

today.

Something very similar happened in response to the Industrial

Revolution of the late nineteenth century, as mass production

became mechanized and stand-alone factories gave way to larger

corporations. Once again, tried-and-true ladders to the middle class

disappeared; once again, a sense of social upheaval led to the frantic

construction of institutions. By now, education was becoming the

clearest path to the middle class for many families. They began

clamoring for high school diplomas for their children, and the then-

ascendant administrative progressives decided it was urgent that

someone weigh and sort these students. As we’ve seen, their

methods were less impartial than they supposed, and we still live

with many of the structures and practices they laid down—including

the educational winnower.

Today, we’re experiencing a moment remarkably similar to those

earlier watershed periods. Income mobility, as Flowers pointed out

in his address, has stagnated. Automation in the workplace is

claiming certain types of jobs while opening up new ones, a

remarkable parallel to what happened over the course of the

nineteenth century, when mass-production-by-hand gave way to

mass-production-by-machine. The regional market revolution of the

early nineteenth century, too, is a notable antecedent for today’s

global flow of jobs, people, and goods (the last of which I suppose

I’ve contributed to as much as anyone, considering RFID’s role in

greasing the wheels of global trade). As the cliché goes, trade helps

more people than it harms, but it does create winners and losers,

and it can move once-reliable economic ladders out of sight when

you’re not looking.

These conditions, combined with the rapid pace of technological

change, demand an education that is simultaneously able to keep up

with the times, yet also timeless. As Max Ventilla put it, the

aphorism “Give a man a fish, he’ll eat for a day; teach a man to fish,

he’ll eat for a lifetime” makes a degree of sense—“but that’s

assuming that the way that you teach him how to fish stays relevant

for the rest of his life.” Even as the specific rules of how to earn a

living change, however, broad skills never go stale. To the list of

such classics as “learning to learn” I’d add comfort in the face of

complexity, control over one’s own working memory, and, perhaps

most important, to use Flowers’s term, the development of a

creative ego. That doesn’t mean we should give up on direct,

subject-specific training, but such training must become more

forgiving in terms of learners’ time, location, and money, and more

agile in the face of change. What we need is a patchwork approach—

a mens et manus approach—to give students both the hard facts

they’ll need to understand the world and the hands-on skills they’ll

need to wield them: to think using calculus. The MicroMasters to

master’s progression is an example of a two-part patchwork quilt,

but it’s far from the only possible model.

If we do soon experience yet another major educational

reshuffling, the timing couldn’t be better, because it might give us

the chance to root out and replace the antiquated notions still

influencing how we’re expected to teach and learn. Thanks to the

unceasing work being done up and down the high-rise of the

cognitive science disciplines, we now have the capacity to structure

instruction that doesn’t interfere with the biological and

psychological processes underlying learning, but rather supports

them. And thanks to new, often (but not always) tech-enhanced

tools and methods, we can take such approaches and make them

both more widely accessible and more flexible, tolerant of the

differences that make us unique.

Perhaps most crucially: Only today do we have the advantage of

hindsight. We may finally have the historical perspective we need to

avoid the mistakes of prior generations of educationalists. As

William James wrote in 1899, “Psychology is a science, and teaching

is an art; and sciences never generate arts directly out of

themselves. An intermediary inventive mind must make the

application.” We must think about learning not only as scientists,

but also as appliers of that science: designers, engineers, artists,

teachers, learners. By so doing—with a modicum of decisiveness

and a minimum, I hope, of hubris—we can improve lives in a

tangible way, and direct more of the world’s latent potential toward

the hard problems we face.

For too long, we’ve blindly obeyed educational traditions built on

precarious scientific evidence, and consequently impeded learning

everywhere. Now, the opportunities presented by a more intentional

approach—to place learning above winnowing; to place access above

exclusivity—are too promising to ignore. There is no better day than

today to announce a new age of learning. Before the hour grows any

later, let’s fire off a cannonade not of gunpowder but of action

potentials and get started.

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—Sanjay Sarma and Luke Yoquinto