Near-misses and failure (part 1)

Drawing on two high profile examples, Sean Brady suggests that attitudes toward near-misses can sometimes result in complacency – with catastrophic consequences.

A recent article in the Harvard Business Review, entitled *How To Avoid Catastrophe*[1], explored how understanding the causes of 'near-misses', can play a key part in anticipating the more significant failures. The article, by Tinsley, Dillon and Madsen, examined failures from a diverse range of industries, including BP's Deepwater Horizon oil blowout in the Gulf of Mexico and Apple's issues with poor signal strength following the release of the iPhone 4 in 2010.

While failures of a structural engineering nature were not specifically discussed, it is interesting to examine if near-miss concepts can be applied by the structural engineering profession to better anticipate catastrophic failures. The fundamental characteristics of near-misses are presented in this article, and, in the next issue, their potential application to structural engineering is explored.

Near-misses can be defined as successful outcomes where chance plays a critical role in averting failure[2]. In other words, they are situations where latent issues exist, that have the potential to cause significant failures when subject to certain enabling conditions, but where good luck has, to date, prevented such enabling conditions from occurring.

Such a concept is, of course, well known to the workplace health and safety profession, who typically require both workplace incidents and near-misses be recorded. Near-misses are simply viewed as accidents waiting to happen, with good luck having played a key role in preventing an incident to date.

Toyota

The concept of near-misses is clearly illustrated by the issues faced by Toyota in 2009, when a Lexus sedan, which was manufactured by Toyota, experienced uncontrolled acceleration issues and crashed, leading to fatalities. A subsequent investigation discovered latent issues with Toyota's acceleration system, which resulted in the withdrawal of 6 million vehicles and a loss in sales of $2 billion to Toyota in North America alone[1].

Was there an opportunity for Toyota to identify this latent issue prior to the fatal crash? Figure 1 shows the percentage of complaints relating to acceleration issues for a specific vehicle[1]. Firstly, for the Honda Accord, the percentage of complaints relating to acceleration issues from 1995 to 2010 was typically less than 10% of the overall complaints received for the vehicle. (Apparently this is a typical percentage, and upon investigation is found to generally relate to driver error, rather than a vehicle defect).

Figure 1
Totota customer complaints relating to speed control (1995-2010)

However, for the Toyota Camry, the percentage of complaints relating to acceleration issues dramatically increased from less than 10% in 2000 to almost 50% in 2009. Given that Toyota introduced a new acceleration system in 2001, this deviation from a typical percentage of complaints relating to acceleration should have suggested there was a significant issue with the new accelerator system. Indeed, Tinsley et. al. argue that each of the complaints was a near-miss, as each complaint was an incident where uncontrolled acceleration occurred (the latent issue), but a catastrophic crash did not result (due to an absence of enabling conditions). Those near-misses continued to accumulate until luck ran out in 2009, and the tragic crash occurred.

Why were these warning signs ignored? Fundamentally, Tinsley et. al. conclude that people are hardwired to misinterpret or ignore such warning signs, resulting in them not being investigated. Two issues particularly come into play that cloud judgement: Normalisation of Deviance and the Outcome Bias.

NASA

Both of these cognitive biases are illustrated by NASA's Columbia disaster in 2003, when the space shuttle Columbia disintegrated upon re-entry, with the loss of the shuttle and all seven crew[3]. The technical cause of the disaster was a failure of the shuttle's Thermal Protection System (TPS), which allowed hot plasma to enter the shuttle's wing structure, causing it to structurally fail, with subsequent loss of the shuttle. The investigation found that the TPS had been damaged during lift-off, when a briefcase-sized piece of foam became detached from the main fuel tank and impacted the shuttle's left wing (Figure 2).

As with Toyota, there was near-miss information available prior to the disaster. The TPS design was based on the assumption that it would not be subject to debris impact. Debris impact had potentially disastrous consequences, namely loss of the shuttle during re-entry. However, it was clear from video footage that debris was impacting the TPS during previous flights in the shuttle program[3]. Furthermore, based on shuttle inspections following mission completion, it was confirmed that damage

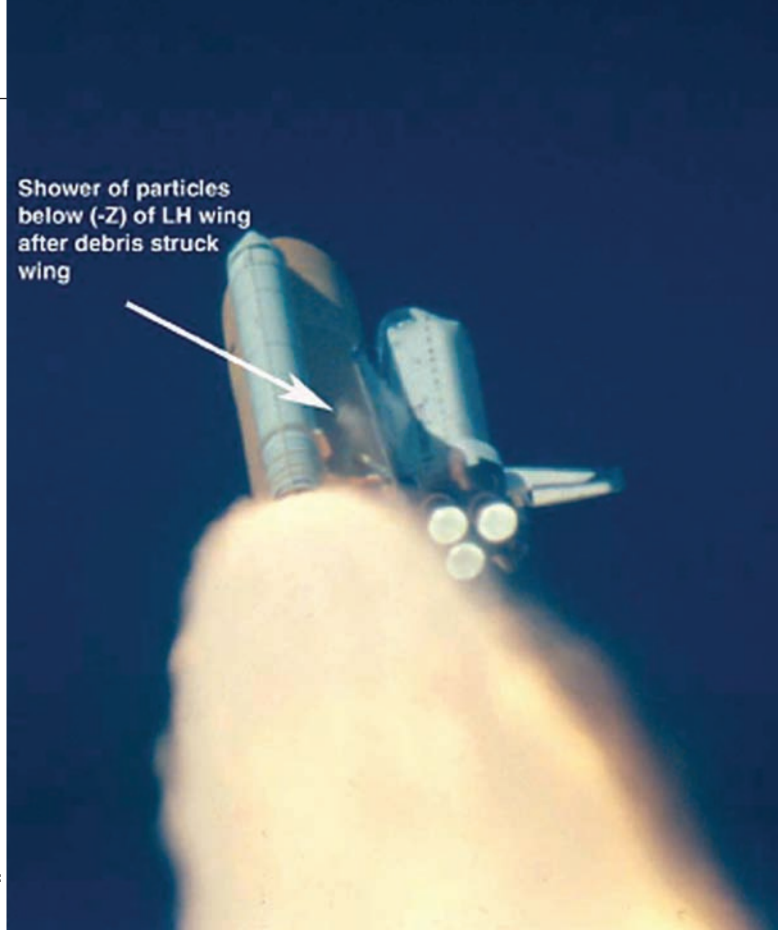

Figure 2 Space shuttle Columbia: detached foam impacting left wing

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was indeed occurring to TPSs as a result of these impacts[3].

Therefore, in near-miss terms, there was a 'deviation' between expected performance (no impacts) and actual performance (impacts occurring). Each launch was a near-miss, with good luck intervening to prevent a large enough piece of foam from impacting the shuttle's TPS at a critical location. Why then, given the potential catastrophic consequences of such a deviation, was it ignored?

Normalisation of Deviance

Near-miss research shows that when human beings become familiar and comfortable with a risk (or deviation) it becomes normalised, i.e. what was once a concern becomes acceptable[1]. In NASA's case, the engineers were aware that the TPS debris impacts were a deviation, and this caused initial concern. However, with every successful launch and return, despite the debris impacts, engineers and NASA management became more comfortable with the impacts, and they became normalised[3]. In effect, rather than being treated as evidence that the potential for catastrophic failure existed, the near-misses were viewed as supporting the position that catastrophic failure was unlikely. Once deviations are normalised, the opportunity to learn from them is generally lost.

Outcome Bias

While there is obvious wisdom in investigating and understanding the causes of failures (although it doesn't always occur in practice), research indicates that the causes of successes are rarely investigated[1]. Near-misses, unfortunately, appear to be typically treated as successes, rather than failures, and remain un-investigated. For example, NASA categorised shuttle launches with debris impacts as successful missions, despite their potential for catastrophic failure. The debris impacts effectively came to be viewed as an ordinary occurrence, becoming a maintenance issue rather than a flight safety issue[3]. Ultimately, NASA observed successful outcomes, and assumed that the process that led to them was fundamentally sound, even when it wasn't[2].

The research indicates that the ability of Normalisation of Deviance and the Outcome Bias to cloud judgement should not be underestimated. Tinsley et. al. stress that across many industries, including NASA, telecommunications companies and automobile manufacturers, multiple near-misses preceded all of the failures they examined, and in most cases, these near-misses were ignored or misread. Indeed, they were often viewed as proof that the system was working, that is, despite the potential for failure, failure did not occur, thus confirming the robustness of the system[1,2].

As a result, the concept of a 'deviation' becomes critical, as it provides a means of rationally challenging these cognitive biases. Returning to Fig. 1, the Toyota Camry's increase in percentage of acceleration complaints can be thought of as a 'deviation'. A key aspect of a deviation is that it is a fact. While arguments can ensue about what constitutes a 'small' failure (and psychology indicates that human nature tries to hide or disguise small failures), a deviation is simply a measurement of the difference between expected and actual performance, and once expected performance is defined and actual behaviour is recorded, a deviation becomes apparent. For example, a paper by Cannon and Edmondson[4] describes an approach taken by Electricite De France, a nuclear power plant operator, to identify and investigate potential near-misses events:

'The organization tracks each plant for anything even slightly out of the ordinary and has a policy of quickly investigating and publicly reporting any anomalies throughout the entire system so that the whole system can learn.'

In the next issue, the application of near-miss concepts in structural engineering will be explored, the process for identifying and investigating near-misses will be presented, and the dark side of possessing near-miss information will be highlighted. In the meantime, the following quote by Edward Rogers, Chief Knowledge Officer from NASA's Goddard Space Flight Center, illustrates how powerful near-miss concepts can be in anticipating failure, even in an organisation such as NASA, which faces major challenges, complexity, and uncertainty:

"Almost every mishap at NASA can be traced to some series of small signals that went unnoticed at the critical moment".[1]

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Near-misses and failure (part 2)

Here, Sean Brady sets out seven strategies for identifying and reacting to structural failure near-misses.

In last month's issue, we explored the crucial role played by 'near-misses' in anticipating significant failures. Near-misses are defined as situations where the potential for failure exists, but good luck intervenes to prevent it. In other words, they are incidents where latent issues are present, but the enabling conditions necessary for failure to actually occur are absent, but may be present in the future. This concept was explored by examining Toyota's withdrawal of over 6 million vehicles due to acceleration issues in 2009 and NASA's Columbia disaster in 2003. Indeed, evidence from a diverse range of industries, including medicine and business, indicates that near-misses provide the early warning signs of impending failures, which, if heeded, have the potential to prevent serious catastrophe[1].

While it intuitively makes sense to investigate such near-misses, research suggests that two cognitive biases, Normalisation of Deviance and the Outcome Bias, can result in these warnings being ignored, typically preventing rational investigation taking place.

So what options are available to overcome these very real barriers? Tinsley *et. al.*[1] present seven strategies, developed in consultation with NASA, to effectively learn from near-misses:

Heed high pressure

Intuitively, it makes sense that at times of high pressure the significance of near-misses is more likely to be missed. Structural design, and certainly construction, can be, by their very nature, high pressure environments. The fundamental issue is that when decisions are made under pressure, there is a tendency to rely on heuristics and rules of thumb, thus increasing susceptibility to cognitive biases. Rationality can simply take a back seat in the decision making process.

Tinsley *et. al.* suggest that one of the fundamental questions to ask when responding to high pressure situations is: 'If I had more time and resources, would I make the same decision?'. If the answer is no, then a more objective assessment of risk is required.

Learn from deviations

A deviation is defined as a difference between expected and actual performance. A key advantage of a deviation is that it is a measurable fact, rather than an opinion; once expected performance has been defined, and actual performance measured, the deviation is simply the difference.

The concept of deviation is powerful, because its factual nature removes emotional arguments over what constitutes a failure, and focuses discussion on the potential causes and consequences of such a deviation. Ultimately, Tinsley *et. al.* suggest that individuals should seek out deviations from the norm and ask 'Why am I willing to tolerate this risk?'

Uncover root causes

Building on the previous point, unless the root cause of a deviation is understood, it is difficult to evaluate potential consequences. Unfortunately, the literature suggests that there is often a greater focus on addressing symptoms, rather than identifying cause. This is a normal human reflex, but a failure to identify causation is a missed opportunity to identify potentially latent errors.

Demand accountability

Research indicates that a useful way of assessing near-misses is to do so in a formal manner. When assessments of near-misses have to be justified, our perception of them changes. In other words, by having to defend our assessments, we become more objective in our approach, and we are more likely to view near-misses for what they are: small failures.

Consider worst-case scenarios

It is human nature not to consider worst case scenarios unless specifically required. By purposefully thinking about worst case scenarios, however, we articulate consequences and can adjust our decision making process.

Evaluate projects at every stage

The benefit of investigating why a project stage fails is self-evident, but there is also benefit in evaluating why project stages are successful. Such an exercise forces a rational assessment of why success was achieved, thus challenging the Outcome Bias and identifying where good luck has played a central role, thus unmasking potential latent errors.

Reward owning up

The research indicates that actually getting individuals to report near-miss information is highly problematic. For many individuals, reporting near-misses is akin to owning up to failures, and they are concerned about potential repercussions. Putting in place a culture where individuals not only feel safe to report near-miss information, but where it is actively encouraged, is fundamental to developing a culture of learning from near-misses.

Near-misses and structural engineering

So are such near-miss concepts applicable to structural engineering failure?

While it is, of course, a matter of opinion, there is plenty of evidence to support its applicability. When made aware of near-miss concepts, most engineers can point to situations in their career where near-miss information was ignored, despite its potential importance being recognised. It is dealing with these situations where organisations like Structural Safety (formally SCOSS and CROSS) play a critical role in assembling, analysing and interpreting this type of near-miss information to keep the profession aware of potential latent errors in how we approach the design and construction process. Indeed, the broader near-miss research would support the position that Structural Safety should not be considered as a useful 'add on' to the profession, but rather as an integral part of being genuinely committed to minimising the risk of structural failure.

When the significant structural collapses are examined, a similar trend in a failure to utilise near-miss information is discovered. For example, returning to the 30 year failure cycle evident in catastrophic bridge failures, as discussed in the May 2013 issue, authors Sibly and Walker highlighted that almost all of the key bridge failures they examined were preceded by near-misses that went un-investigated[2]. For example, prior to the collapse of the Tacoma Narrows Bridge, there were numerous incidents of unexplained vibration in suspension bridges, including the Golden Gate Bridge. Further, Petroski, in *To Forgive Design: Understanding Failure*[3], stresses that a similar trend of near-miss type information is evident in cable stayed bridge design. The Anzac Bridge in Sydney and the Pont De Normandie in France exhibited undesirable vibration issues which required retrofitting. One can, of course, argue that the profession is interpreting these events as near-misses, thus heeding the warnings, but history, unfortunately, cautions against such an assumption. Petroski suggests that there may be a growing perception that such vibration issues can simply be managed, and this is classic normalisation of deviance. Further, the Outcome Bias could be, naturally, attributing the success of such bridge designs to sound engineering, with the role of good luck remaining unknown. There are clear echoes of NASA's Columbia and Challenger disasters in such discussions, with arguments to the contrary being inconsistent with structural engineering history.

Closure

As we have seen, near-miss information can certainly play a key role in averting the larger failures in structural engineering, as well as in other professions and industries. There are significant challenges in collecting and analysing such information, and organisations such as Structural Safety have a key role to play in ensuring such information, which is typically sensitive, is disseminated appropriately.

However, there is also a dark side to possessing near-miss information. Research indicates that possessing near-miss information can lead to riskier decision making than in its absence. While this may appear counterintuitive, the phenomenon is rooted in human nature, particularly in how we perceive risk. Dillion *et. al.*[4] use the following example to illustrate the issue:

Imagine you join a social club that meets in an unsafe part of the city, where there is a statistically higher than average probability of being mugged. If you were to attend a number of meetings and not be mugged, nor witness anyone else being mugged, then you are likely to feel safer, and perceive less risk. This is the key point; each visit to this part of the city is essentially a near-miss because the statistical probability of being mugged has not decreased, but your 'perception' of the statistical probability has decreased. In other words, you are likely to be less vigilant (and less risk adverse) than someone who is not in possession of similar near-miss information. As with all information relating to failures, caution is required.

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Hartford stadium collapse: why software should never be more than a tool to be used wisely

While we may think of blind faith in technology as a modern affliction, Sean Brady's account of the Hartford Civic Center Stadium collapse shows that overreliance on structural analysis software is not a new problem.

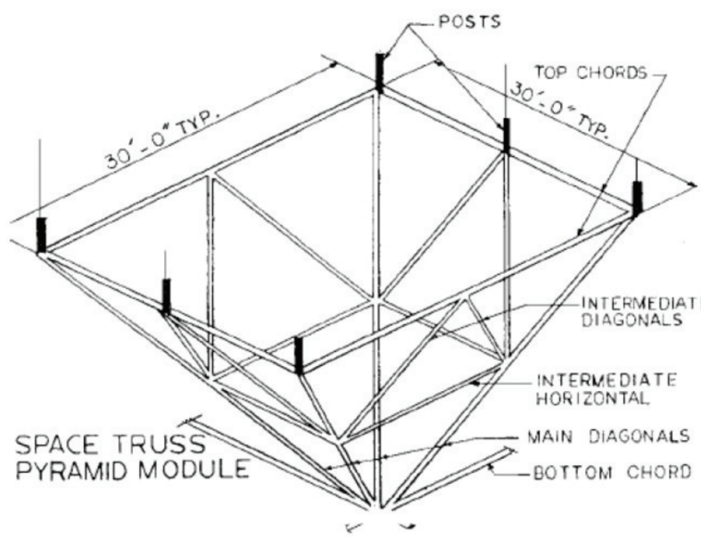


Figure 1 Space frame module for Hartford Civic Center Stadium

(1 ft. = 0.305 m)

ATTRIBUTED TO LZA

Introduction

Picture the scenario: it's 1971 and you've just received your new, state-of-the-art, structural analysis software package. It's exciting, especially given it was purchased specifically for the design of a complex, large stadium roof. This will be a fantastic opportunity to demonstrate what can be achieved once you have the right technology.

You complete your design, but as construction progresses, concerns are raised. Your roof is deflecting more than you anticipated. Your design is queried. You explain that there is no need to worry because discrepancies between predicted and actual deflections are to be expected – you're not concerned because you used a state-of-the-art software package. Then you're informed that installation of the roof's fascia panels is proving problematic due to the level of distortion in the structure. The fascia support brackets don't fit as intended. So the contractor adjusts the support brackets, and again you remain unconcerned by the distortion because your design was completed using a state-of-the-art software package. Then a number of members of the public complain that your structure appears to be excessively deflecting. So the client raises these concerns with you, and you put them at ease. After all, you remind them, your design relies on a state-of-the-art software package.

At this point, reading this article, you're probably protesting that you'd do no such thing. You'd probably argue that you'd heed the warnings, you'd revisit your software model, and you'd get to the bottom of why there was such a difference between predicted and actual performance. You certainly wouldn't brush off repeated concerns. In fact, you're probably wondering why we're discussing such a far-fetched hypothetical scenario in the first place.

But just because it's far-fetched, doesn't mean it's hypothetical.

Hartford Civic Center Stadium

The roof of the Hartford Civic Center Stadium, in Connecticut, USA, was an ambitious design – a 91.4m × 110m space frame suspended 25.3m above a 10 000 seat arena. It would be supported by only four pylons, each offset from the roof's edge, creating a 13.7m wide cantilevered perimeter. It would have 2300 members, and be comprised of a grid of 6.4m deep, 9.14m × 9.14m modules (Figure 1)[1].

These modules had a number of key features. Firstly, the roof panels were not attached directly to the top chords, but instead were connected to posts protruding from these chords at discreet nodes. By using posts of differing heights, a drainage gradient in the panels was achieved, and these posts would also minimise bending moments being transferred from the roof panels into the space frame. Secondly, diagonal members were included to provide lateral support to the top chords, intended to reduce their unbraced length from 9.14m to 4.57m. Thirdly, this lateral support was critical, as the top chords were comprised of four steel angles formed in a cruciform – a cross-section inherently weak in buckling.

In order to complete the design, the structural design firm, Fraoli, Blum & Yesselman, did indeed use a state-of-the-art software analysis package[1]. In fact, they convinced the city of Hartford to purchase the package, citing construction savings of half a million dollars through its use. Once the design was completed, the Bethlehem Steel Company was awarded the construction contract and an inspection and testing agency, Gulick-Henderson, was engaged to ensure satisfactory completion. Construction began in 1972, with the space frame, along with all services, such as electrical conduits and ventilation ducts, being assembled at ground level, then jacked up into position – a novel approach at the time.

Concerns

However, when the space frame was assembled (and still at ground level), Gulick-Henderson informed the designers that it was deflecting more than the 310mm expected. The issue does not appear to have been addressed, and it was jacked 25.3m up to the top of the pylons. At this point the maximum sag was measured and found to be not only larger, but twice that expected. Given the news, the designers replied that such discrepancies had to be expected in view of the simplifying assumptions of the theoretical calculations[2].

It was then that the contractor installing the fascia panels discovered that the space frame was significantly distorted, with the holes for the fascia support brackets not lining up with the space frame. The designers again expressed no concern, and the project manager reminded the contractor that they were responsible for all delays on the project. The contractor then cut/extended the brackets and welded them into place, essentially working around the distortions.

Multiple complaints were indeed received from members of the public – apparently the roof deflections were so pronounced that they were clearly visible and unsettling[2]. The city of Hartford, concerned, approached the designers, who again defended the adequacy of their design.

Fast-forward five years to the night of 18 January 1978, when the Civic Center was subject to its heaviest snow load since construction – heavy, but still only half the design load. At 4:19am that morning, with the arena empty, the 1270t space frame collapsed in its entirety (Figure 2). What is truly disturbing, however, was that only six hours earlier, over 5000 people had been sitting below it, watching a basketball game.

Cause

The investigation that followed was conducted by Lev Zetlin Associates, Inc. (LZA), who would conclude that the structure essentially began failing as soon as it was completed[1]. There were a considerable number of design deficiencies, which are discussed comprehensively by a number of other authors[1,2]. We will focus on the primary issue, the buckling capacity of the top chords, specifically the level of restraint provided by the bracing diagonal.

The key problem was an assumption. While the designer – and software package – utilised an unbraced length of 4.57m for the top chords, the investigation would discover that this was far from the case in practice. As the diagonal bracing was in the same inclined plane as the top chords, deflection was only restrained in one plane – the external top chords were essentially free to deform out-of-plane horizontally. Further, the absence of a post at some of these locations removed any potential restraint that the roof panels may have provided (Fig. 1). While the software package assumed an unbraced length of 4.57m, in reality the top chords were found to be essentially unbraced, with a length of 9.14m. The issue was further exacerbated by changes in the diagonal-to-top-chord connection details, where the diagonal connection points were not coincident with the top chords (Figure 3).

These issues resulted in a significant overload: the exterior top chords on the north-south face and east-west face were overloaded by 213% and 852%, respectively. Once the top chords buckled, the progressive collapse of the space frame resulted.

Figure 2
Collapsed space frame

PA

Dangers of software

Few of us need to be warned about the dangers of overreliance on software packages – it's something that most experienced engineers worry about and it's drummed into every young engineer using such packages. (Simple, quick, hand calculations to check model results are still the key in combating overreliance – there's an argument to be made that every analysis package should come with a complimentary copy of *The Structural Engineer*'s *Pocket Book*[4] and *Roark's Formulas for Stress and Strain*[5].)

However, despite our protests that we would not have blindly kept faith in our analysis results, but maintained a healthy scepticism, we regularly encounter engineers who insist on the validity of their results, regardless of how a structure may be performing in practice. Such overreliance is not a new problem, and it goes back further than the birth of computer software. One only has to remember Theodore Cooper and the Phoenix Bridge Company's overreliance on analysis techniques when designing the Quebec Bridge in Canada at the beginning of the century. Even when confronted with the partially completed bridge showing clear signs of distress, Cooper and Phoenix refused to believe their analysis methodology was flawed. As a result, 75 construction workers paid the ultimate price[6].

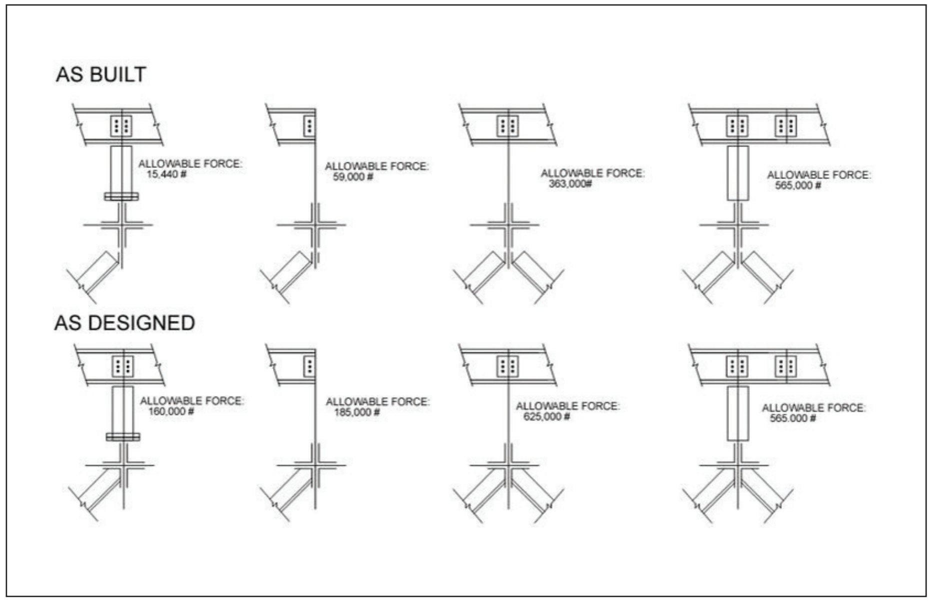
Software packages do, however, add a further layer of complication to this issue. Firstly, our industry spends considerable time and effort training engineers in the use of such packages – time that is often not spent learning, developing and perfecting the use of first principles and hand calculations. Many engineers hold the view that we are training a generation of computer programmers instead of engineers, and it is indeed telling that in the age of advanced analysis, misunderstanding fundamental structural behaviour still remains one of our primary causes of failure.

Secondly, such packages can result in engineers who may not have the appropriate expertise tackling more complex analysis simply because the software allows them to do so. Of course, what is then missing is the experience and expertise to check such analysis.

Thirdly, the sophistication of modern software packages can encourage us to analyse things to a very detailed level, thus stripping conservatism from our designs and, ironically, potentially resulting in 'less safe' designs when compared to more simple but crude hand calculations. Just because we can analyse in minute detail, doesn't mean we should. We should never ignore the fact that, in the hustle and bustle of on-site construction, similar precision may simply not be achievable.

Finally, and perhaps most insidiously, sophisticated software can result in overconfidence. We can start to believe that the more advanced the software, the more correct it is – as humans we tend to equate system complexity with system accuracy, despite the opaqueness it introduces. This is what happened in Hartford: given that the designers specifically argued that they needed the state-of-the-art package to complete the project, why would they then doubt the outputs from that package? To do so was tantamount to doubting the very decision to purchase the software in the first place.

Figure 3
As-built and designed connection details[3]



Readers of June and July's articles on being wedded to our tools[7,8] should not find such behaviour surprising. Analysis methodologies and computer software are tools in our profession, but if an engineer's training is dominated by such tools, they become wedded to them, and are likely to experience difficulty in dropping them, regardless of what the real structure is telling them. These tools can become part of an engineer's identity. Thus, questioning them becomes akin to questioning one's very identity.

New era

Software tools have made an immense contribution to our profession, they have removed many of our more mundane tasks and allowed us – when appropriate – to analyse ever more complex behaviour, but they are only as good as the engineer driving them. As we take our first steps into a new era in the construction industry, what could be called the 'BIM era', we should be excited about the possibilities, the advantages and the efficiencies that computer software, whether it be analysis packages or Building Information Modelling (BIM), can bring. But we must also be vigilant, because their reliability is governed by one important cog in the wheel: ourselves. Hartford teaches us that no matter how state-of-the-art a system is, human error and fallibility have the power to strip away its advantages, sometimes leaving us worse off.

As put so succinctly by journalist Mitch Radcliffe: "Computers have enabled people to make more mistakes faster than almost any invention in history, with the possible exception of tequila and handguns[1]."

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Wedded to our tools: why expertise can hold us back (part 1)

In this two-part article with a difference, Sean Brady looks further afield to explore how 'expertise bias' may cloud our judgement.

Jump

The C-47 flew over the Missouri River and began circling above Mann Gulch, all the time buffeted by strong winds. Wag Dodge, the smokejumper foreman, along with the spotter, Earl Cooley, lay on the floor of the plane and looked out of the open door at the fire burning in the gulch below. It was 3:10pm. It had been a rough ride from the smokejumper base at Missoula, Montana. Most of the 15 smokejumpers squeezed into the plane behind Dodge were eager to jump, anything to get out of the bouncing plane. A number of the men had thrown up. One had taken off his jumpsuit and would fly back to Missoula and resign.

Cooley drew Dodge's attention to a spot on the northern slope, about half a mile from the nearest point of the fire, which now covered 60 acres (Figure 1) – small by US Forest Service standards. Dodge studied the jump spot. They wouldn't be able to land a rescue helicopter if something went wrong, but it would work. Then the pilot spoke in Cooley's earphones: they would be jumping from 2000 feet instead of the usual 1200 – the turbulent winds in the gulch were sucking the plane downwards. There would be more scatter of the men and equipment, but they'd just have to deal with that on the ground.

Dodge stood up and took position by the open door. The rest of the smokejumper crew followed suit. They would jump in 'sticks' – groups of four – with the plane circling back to make another pass over the gulch with each successive 'stick', before finally dropping the cargo. Dodge's static line was snapped onto a rod on the roof of the plane and the other end was connected to his parachute. Cooley remained lying on the floor beside the open door, ready to give the customary tap to the top of Dodge's left calf as the signal to jump – words were useless over the roar of the engine and rush of wind through the open door. Cooley judged the flight speed, wind speed, and all the time kept his eye on the landing spot. He waited for the right moment. Then Dodge felt the tap and stepped out into the air. In five seconds, his static line pulled taut and tore open his parachute. He began the one-minute drop to the ground below.

The temperature was 36°C, the hottest day recorded in nearby Helena since records began. Such heat, when combined with the turbulent winds in the gulch, had the potential to create almost impossible firefighting conditions. And they would. Within two hours of these 15 men parachuting into this obscure gulch on the Missouri River, 12 would be dead or dying, making 5 August 1949 one of the most tragic days in US Forest Service history.

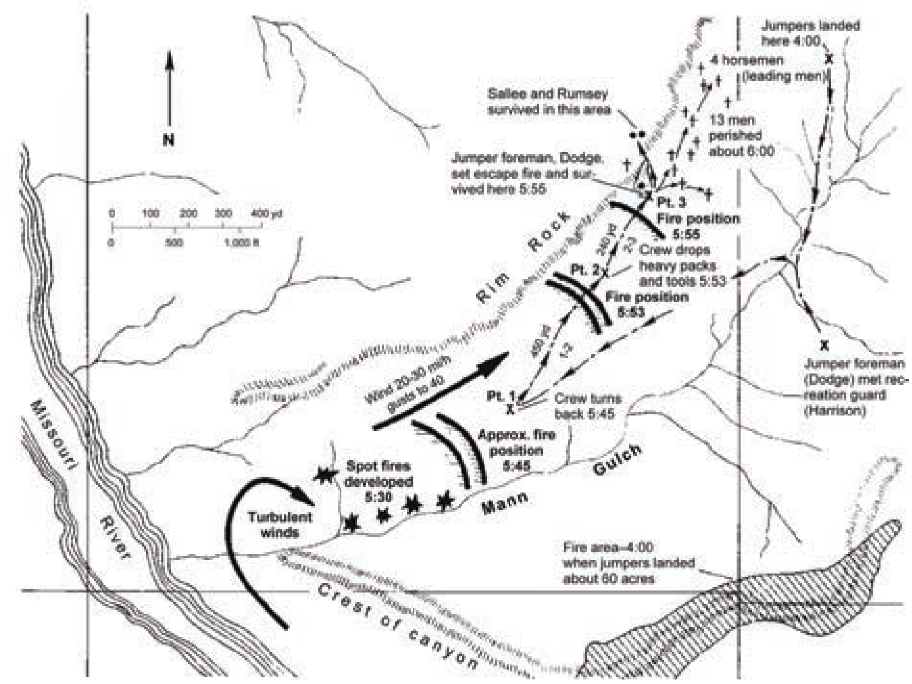

Figure 1 Map of Mann Gulch showing sequence of events

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Mann Gulch

Mann Gulch lies in what is known as the 'Gates of the Mountains' in Montana. This 2.5-mile-long dry gulch, or valley, is bordered by the Missouri River at its foot. Its sides are steep and its northern ridge is topped with a tall rock 'reef' outcrop (Figure 2). To the south of the gulch is Meriwether Canyon and to the north is the ominously named Rescue Gulch. Inside Mann Gulch itself, the southern slope is dominated by thick ponderosa pine and Douglas fir, while the northern slope – which will become central to our story – is covered with waist-high 'bunch' and 'cheat' grass, with the odd patch of trees. To the firefighter, these two slopes create very different challenges. Fire burning among trees tends to burn at a terrific heat, but moves slowly, about 1mph. By contrast, fire on a predominantly grassy slope burns with considerably less heat, but spreads rapidly, sometimes travelling as fast as the wind driving it.

The fire in Mann Gulch had started the day before, when a lighting strike hit a band of ponderosa pine on the southern slope of the gulch, down near the river. The fire was noticed the next day by a nearby lookout and Jim Harrison, a forest ranger. The smokejumpers from Missoula were called and a large team requested, but because all planes but one were on other fires, only Dodge's crew was sent. When Dodge first saw the fire through the open door of the C-47 he wasn't worried. He considered it a '10 o'clock fire' – they would dig a fire line around it that night and have it under control by 10am the next morning.

The smokejumpers considered themselves the elite of the US Forest Service's firefighters. Put together nine years previously, the group's role was to tackle and contain small fires before they grew and became more destructive. With speed being a critical element in their response, parachuting onto a fire was vastly more effective than wasting critical time tracking through rugged country. Their firefighting technique was to create a fire line. Their tools were shovels and saws, along with the all-important Pulaski axe, itself an invention of the Forest Service. The head of the Pulaski had an axe on one side and a hoe on the other, making it perfect for scraping away soil.

The smokejumpers would arrange themselves in a line on the flank of the fire, close to its front, and using the Pulaski dig a shallow trench about three-feet wide, removing all material down to mineral soil, including tree branches and vegetation. Denied fuel, the fire shouldn't cross the fire line, and by controlling its direction of spread they could 'drive' it onto open ground or a rock shelf where it would burn itself out. Mopping up followed, with the jumpers using shovels to dig holes and bury still smouldering logs. This was arduous and dangerous work, and a young man's game. Wag Dodge, the foreman, was the eldest at 33, with many of the crew being around 20. Robert Sallee was the youngest at 17, and underage.

Reconnaissance

All of the jumpers landed safely, then they heard a crash from further down the gulch. The radio's parachute hadn't opened and it was pulverised on landing. With no backup, the jumpers were now cut off from the outside world.

It took until 5pm to retrieve all their gear, then Dodge decided to track down Harrison, the ranger who was already battling the fire. He instructed the men to eat some food, with Bill Hellman in charge. The men ate, then tooled up with packs, shovels, saws and Pulaskis and began to make their way down the gulch towards the fire. Dodge found Harrison at the top of the southern ridge – he had spent the past four hours scraping a fire line to prevent the fire getting into Meriwether Canyon. They chatted, then both joined the crew now on the southern slope.

Dodge didn't like what he saw in the burning trees, nor did he like his men being on the southern slope among the tightly packed timber – the location was a potential death trap. He ordered them to make their way from the southern slope across to the northern slope. They would then make their way down that side of the gulch towards the river, so they could attack the fire's flank. If anything went wrong and the fire changed direction, they could always retreat to the river and seek shelter. As Hellman led the men away, Dodge and Harrison went to get something to eat. The crew crossed to the northern slope and began to make good progress down the gulch. They were feeling good and weren't worried. Dodge, however, eating and watching the fire from a distance, became concerned, to him the fire was about to boil up, and he needed to get his men out of the gulch. Dodge and Harrison quickly re-joined the crew. It was now 5:40pm.

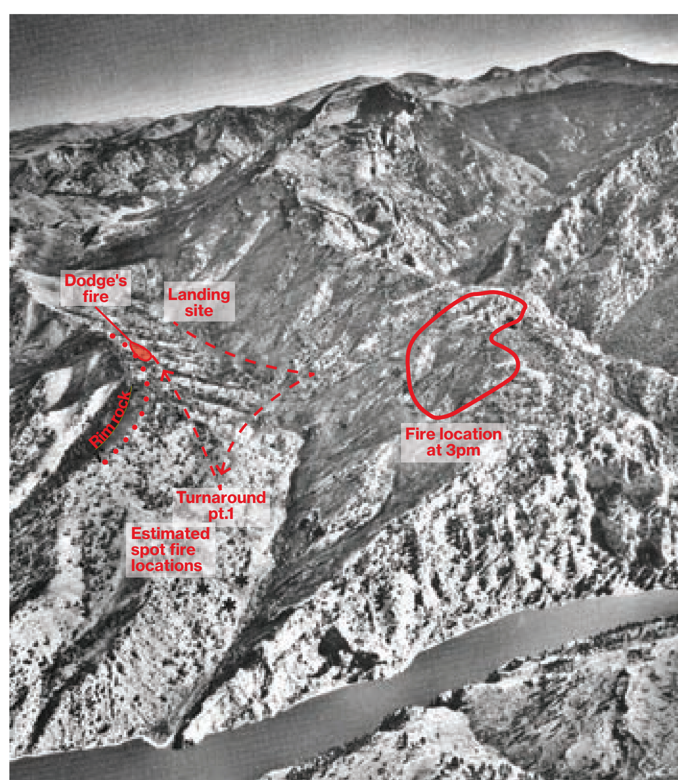
Over the next five minutes they moved down the gulch towards the river, watching the fire on the opposite slope. Black smoke billowed from the trees, and when it occasionally lifted, Dodge saw large tongues of flame among the tightly packed timber. The wind was also starting to pick up to between 20 and 40mph. The heat was intense and Dodge's concern grew.

Blow-up

Suddenly, the fire spat hot embers into the grass at the foot of the northern slope, between the crew and the river (Fig. 1). Dodge saw it immediately, and ordered the men to turn round and quickly head for the top of the ridge – standard firefighting practice, as fire generally slows down at a ridge due to sparse vegetation and turbulent wind conditions. But as the fire spread in the grass and moved towards them, now only 150 to 200 yards away, it became clear to Dodge that this was no ordinary fire: it had an intense heat because of its origin in heavy timber and had speed because it was now in grassland.

Indeed, over the decades that followed, investigations would show that what

Figure 2 Photograph of terrain showing key sites



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happened in Mann Gulch that day was a 'blow-up' – a tornado of fire caused by intense heat, natural winds, along with wind generated by the blow-up itself; the hot air rises and draws cooler air in below, further fanning the flames. While the fire had started slowly and quietly in dense timber that morning, it would now move through the gulch with a stunning lethality and would go on to burn 4500 acres before a team of 450 firefighters would get it under control. For the crew in the gulch, however, their race with the fire would be over in just 11 minutes.

Race

At 5:45pm Dodge gave the order to turn. They had a 150–200-yard head start on the flames, and fire modelling would show that the fire was moving at about 1.3mph, giving them a lead of only four to five minutes[1,2]. Despite the danger, the men remained calm as they moved quickly up the steep slope in waist-high grass still carrying their heavy tools. They were averaging about 1mph, an impressive speed given the terrain, but the fire was moving faster and about to gain speed. In only four minutes, the fire had covered 200 yards and reached the point where the crew turned around. Its speed had more than doubled to over 3mph. Its flames were 16–20-feet high. With the fire 100 yards behind the men, Dodge gave the order to drop all tools – the shovels, the Pulaskis and the saws – so that the crew could run faster. The time was 5:53pm.

Amazingly, many of the crew continued to hold onto their tools. It was as if they simply couldn't drop them. One of the men, Walter Rumsey, remembered pulling a shovel from Eldon Diettert's hand, but even he couldn't drop it, instead looking for a lone tree to lean it against. He remembers the ranger, Harrison, with his heavy pack still on, making no effort to remove it. Harrison didn't even seem to consider that removing the pack would make him faster. It had taken the crew eight minutes to cover the ground from the turnaround order until the order to drop tools. The fire would now cross the same ground in only one minute.

Two minutes later, at 5:55pm, Dodge, then in the lead, broke through a bunch of sparsely packed trees and had a clear view to the ridge above him. It was still 200 yards away and topped with a rock reef that the crew would have to find a gap through. He realised that the crew wouldn't make it. While the men had increased their speed to 4mph, the fire was moving at almost 7mph, with flames 30-feet high and a fire front 200–300-feet thick. It was as if the wind itself was on fire. The air was black with smoke, Dodge's lungs were burning from exhaustion, and noise from the flames meant that even while shouting it was hard to communicate with the men.

It was then Dodge did something remarkable, believed to be the first use of a technique that has since become standard practice for wildfire fighters. He lit an escape fire (Fig. 1). Taking a match, he lit the grass in front of him and watched flames race up the slope, burning swiftly through the grass. As the crew caught up with him, he shouted at them to get into the ashes before him. Rumsey and Sallee, then leading, had no idea what he meant and thought he was mad to light another fire. They ignored him and continued running for the ridge. Dodge continued to call to the men, telling them to get in the ashes. Then through the smoke he heard someone shout "to hell with this, I'm getting out of here"[2]. From then on all the men just ran past, fixated on getting to the ridge. With a wall of flame bearing down on him, Dodge wet his handkerchief and tied it round his face. He stepped into the ashes and lay face down. Just three minutes had elapsed since the order to drop tools. It was now 5:56pm.

Sallee and Rumsey made it to the ridge and looked back. They saw the crew running past Dodge. The fire seemed to be all around them and had a deafening intensity. Then they watched Dodge lie down and the flames pass over him. In a period of just 60 seconds, the fire would go on to swallow Robert Bennett, Philip McVey, David Navon, Leonard Piper, Stanley Reba, Marvin Sherman, Joseph Sylvia, Henry Thol Jr., Newton Thompson, Silas Thompson and James Harrison, the ranger. Their time of death occurred sometime between 5:55pm and 5:57pm, estimated from the melted hands on Harrison's watch.

Sallee and Rumsey jumped through a crevice in the rock reef, not knowing whether it would lead to safety or trap them with the flames. Diettert was just behind them, but he paused at the crevice, seemed to decide against it, and instead made his way further along the reef. He didn't find another gap and the fire caught him.

Once through, Rumsey sat down beside a juniper bush. Sallee simply looked at him and said nothing. Then Rumsey seemed to realise that to sit there was to die, and he got up. They moved down the ridge and into Rescue Gulch. Then the fire poured over the top of the ridge and flowed towards them. They would survive by finding shelter on an exposed rock slide, moving around on it as the fire burned past them before dying out further down the slope.

Aftermath

For five long minutes the fire front passed over Dodge. He was lifted from the ground two or three times by its updraft. He was saved by the 18in. high layer of oxygen above the ground that the fire couldn't steal. When it moved beyond him he stood up, red eyed from smoke and covered in soot. It was 6:10pm. He looked up and down the slope. It was a barren wasteland. All was silent apart from the staccato explosions of trees that had been superheated by the fire. Then he heard moaning. It would turn out to be Sylvia, horrifically burned and drifting in and out of consciousness.

Sallee and Rumsey would stand up on their rock slide and see Hellman stumble into Rescue Gulch. Somehow he had made it through to the ridge and through the rock reef after being burned by the flames. He collapsed and they did their best to comfort him. Hellman asked Sallee to give a message to his wife, but afterwards Sallee couldn't remember what it was.

Eleven men died in the gulch, mercifully killed by lack of oxygen before the flames reached them. The death toll would go on to rise to 13 – both Sylvia and Hellman would die from their injuries before noon the next day. Only Dodge, Rumsey and Sallee walked out of the gulch alive.

Three questions

While there are many questions we can ask about Mann Gulch, we will start with three. Firstly, why did the crew continue to carry their heavy tools, slowing themselves down, and almost guaranteeing their death? Secondly, why did the crew ignore Dodge's escape fire and keep running for the ridge? Finally, what does a wildfire in a gulch over 60 years ago have to do with the business of engineering?

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Wedded to our tools: why expertise can hold us back (part 2)

Sean Brady concludes this two-part article with a warning to engineers not to become over-reliant on their 'tools', but to consider how and when to apply them.

Introduction

The rescue would go on all night, and when the sun rose over Mann Gulch at 4am, Dodge, Rumsey and Sallee would look down over the barren, burned slope where they'd raced with fire. The grim task of identifying and recovering the bodies of the 11 firefighters who had perished was in progress. The two other survivors, Hellman and Sylvia, were taken away, but they would die from their burns before noon that day (Figure 1). Dodge had survived by lying down in an escape fire but, despite his orders, his men had ignored him and continued to clamber up the steep side of the gulch – many still clutching heavy tools – attempting to get to a ridge that was out of reach. Only Rumsey and Sallee would just beat the flames and make it to safety.

Why did so many of these men cling to their heavy tools as the flames bore down? And why did they ignore Dodge's escape fire and continue running, even though it should have been obvious to them that they would never make safe ground?

The easy answer to these questions, of course, is that the crew simply **didn't think at all**. But to stop our analysis of the tragedy at this point is to miss the underlying reasons **why** they stopped thinking. Was it fear alone or was something deeper at play? While few of us will have to outrun a wildfire in our professional engineering careers, what happened in Mann Gulch was much more than a fire, it was a lesson in how we, as humans, make decisions under pressure. Understanding the reasons why we can abandon rationality is one of the keys to preventing engineering failures.

ALAMY

Figure 1
Memorial to firefighters who died at Mann Gulch

Priming and fixation

We will first fast-forward to the 1990s, to the University of Pittsburgh, Pennsylvania, where Jennifer Wiley would undertake a number of fascinating psychological experiments[1]. Wiley was interested in how **priming** affects our ability to think clearly. Priming, in psychological terms, is when an individual is subjected to a background factor, which then puts that individual in a specific psychological state that affects their subsequent actions, in some cases without them being aware of it. One of the most important and comical illustrations of priming was carried out by psychologist John Bargh at the New York University, and became known as the 'Florida Effect'[2].

Students, aged 18–22, were divided into two groups, with each group being required to make four-word sentences out of scrambled five-word sentences, e.g. 'finds he it yellow instantly' could become 'he finds it instantly'. One group, the control group, was given sentences comprised of random words, but the other group was given sentences that contained some words directly related to being elderly: words like 'bald', 'wrinkle' and 'Florida'. The experiment commenced with each group unscrambling their sentences, and they were then directed to leave the room and walk down the corridor to another room. The outcome of the experiment actually occurred in the corridor, as opposed to either room. Incredibly, the experiments showed that the group that unscrambled sentences containing the elderly themed words walked slower down the corridor than the control group. In effect, the elderly themed words **primed** the students to behave in a more 'elderly' fashion[2].

Psychologists have conducted many experiments to illustrate how powerful priming can be, such as how negative priming can result in poorer performance during cognitive tasks[1]. In Remote Associate Tasks (RAT) tests, an individual is provided with three words, then asked to identify a fourth word that can be combined with the other three words to make a common word or phrase. For example, the words 'blue', 'knife' and 'cottage' are given to the individual. The individual then comes up with the fourth word, in this case 'cheese', giving 'blue cheese', 'cheese knife' and 'cottage cheese'.

However, in some cases individuals were first primed with random words prior to sitting the RAT tests, and they subsequently performed poorer when compared to un-primed individuals. These priming words essentially caused individuals to suffer from fixation, a fixation that was both hard to overcome and set individuals on solution paths that were unsuccessful. (The experiments showed that incubation, taking time away from the problem and then returning to it, was most effective at overcoming the fixation. Time away allowed individuals to 'forget' the priming words, thus freeing up their thinking process to reach the correct answer. This, of course, is one of the reasons why we can so often solve tricky problems in the shower or while driving home from work – we are incubating the problem, allowing our minds to forget the negative priming effects, thus removing the fixation and freeing up our thinking to reach an appropriate solution.)

Domain knowledge priming

Wiley, however, was interested in an intriguing twist to the concept of priming. Rather than individuals being primed to cause fixation, what if the participants, by their existing knowledge, primed themselves? What if the domain knowledge or expertise that the individual possessed prior to the RAT tests was enough to negatively prime them? Wiley set out to answer these questions[1].

She selected knowledge of baseball as the priming 'expertise' or 'domain knowledge'. In the experiments, individuals with both low and high levels of baseball knowledge were subjected to RAT tests. The words in the RAT tests were carefully selected to contain baseball terms so that individuals with a high level of domain knowledge in baseball would activate their knowledge and become fixated. This fixation would set them on incorrect solution paths. Wiley theorised that those with a low level of baseball knowledge would not be primed and therefore would perform better on the tests.

> **"IN PURSUIT OF KNOWLEDGE, EVERYDAY SOMETHING IS ACQUIRED; IN PURSUIT OF WISDOM, EVERYDAY SOMETHING IS DROPPED"**
> **LAO TZU**

She was right. The high-knowledge participants did considerably worse in the tests than the low-knowledge participants. The low-knowledge participants had little or no baseball knowledge to recall, did not get primed, and did not get fixated on futile directions when looking for a solution. Wiley had demonstrated that the possession of knowledge or expertise, when it is not directly beneficial to your current task, can actually be a disadvantage.

And here is where it gets really interesting. Wiley examined whether it was possible to 'switch off' this expertise. Can you 'decide' to not use your expertise? In the next set of tests the participants were told that the RAT tests would contain many references to baseball. They were then warned that they should not use any knowledge of baseball they possessed as it would not be helpful in completing the tests. What happened? Despite the warning, the high-knowledge individuals did just as badly as they did when they received no warning. The warning was useless, with the experiments illustrating that it is simply not possible to 'switch off' your knowledge and expertise. Its use is automatic and it appears to occur subconsciously.

Mann Gulch

We see these very cognitive concepts at work in Mann Gulch on the afternoon of 5 August 1949. Many of the men still clung to their heavy tools, despite being able to run faster without them, and despite Dodge's order not to do so. It turns out that this form of behaviour is not an isolated event. At least 23 wildfire fighters died in fires from 1990 to 2007[3]. Many died within a few hundred yards of their safety zones and a number were found still wearing heavy backpacks with their chainsaws beside them. They too were in a race with the flames, and they too didn't drop their tools.

Fundamentally, these men didn't drop their tools any quicker than the baseball experts dropped their knowledge. They simply couldn't. Indeed, placing total faith in our expertise is fundamental in human nature, especially in stressful situations. Herbert Simon, winner of the Nobel Prize, identifies the issue as **bounded rationality**, where a human mind has limited information processing and storage capabilities, and so humans must use simple rules of thumb and heuristics to help make decisions and solve problems[4]. These rules of thumb and heuristics are our very tools, but Daniel Kahneman and Amos Tversky, both psychologists, point out that many heuristics, or simple rules, that people use to make judgments and decisions lead to systematic and predictable errors[5]. Are we as engineers in danger of making systemic and predicable errors because of our simple rules and heuristics?

The answer, of course, is yes. We carry tools and rely upon them, and Mann Gulch teaches us that when we come under pressure we will rely on these tools even when we should not.

Engineering tools

So, are there times we should drop our tools? And if we do, what are we left with? Well, that depends on the tools we actually carry, as individual engineers. Are our tools engineering first principles? Or are they the systems and processes we use to deliver engineering as a service? If it is the latter, we should give our tools some serious thought. Yet many of us don't, we simply get on with the business of applying them.

And we carry an increasing number of 'non-first principle' tools. We have become dominated by ever more prescriptive design codes, ever more complex in-office procedures, and we are using ever more elaborate software packages. While many engineers make the valid argument that many of these tools prevent errors, many other engineers make the equally valid argument that these tools actively contribute to creating errors – software analysis tools are a prime example. Are these tools aiding us to become better engineers or are they replacing us, at least in a cognitive sense, as engineers? Many were intended to act as aids, but in the ever more commoditised world of delivering engineering services, the focus on the use of such tools is becoming greater and greater, to the detriment of fundamental principles.

Mann Gulch teaches us that when engineers find themselves in unusual situations and under pressure, they will apply these tools regardless of applicability. Indeed, if we become dependent on their use, we may find ourselves in situations where these tools have exceeded their limits without us knowing it. The history of engineering is littered with failures caused by precisely this issue. Developing an awareness of the tools we carry, an awareness of the limitations they come with, and understanding when it is appropriate and inappropriate to drop them should be central for every engineer.

And what happens if we do learn to drop them? Well, we are left with the fundamental principles of engineering. Karl Weick, an expert in organisational behaviour, neatly sums up the advantage of dropping tools from a general perspective: learning to drop one's tools is to gain lightness, agility, and wisdom[3].

This is precisely what Dodge did when he broke through the tree line and realised the top of the ridge was out of reach. He had already dropped his physical tools, now he would drop his mental tool – his fixation on reaching the ridge. Running for a ridge is one of the tools used by the US Forest Service to escape harm – the ridge has less vegetation and changing wind conditions, both of which serve to slow down a fire. Usually, this is good tool, but Dodge figured out in this particular circumstance that the tool was useless. So he dropped it. He was then left with his basic principles: fire required heat, oxygen and fuel. So he decided to deprive it of fuel. He lit an escape fire, the first time it had ever been attempted, inventing a new tool in the process. He was only able to do this because he dropped the other tools. He showed extraordinary agility in his thinking about the issue, exactly what Weick describes.

The rest of the crew's response to Dodge's escape fire shows just how hard our tools are to drop. Not only had they not dropped their tools – while some had dropped their physical tools, none appear to have dropped their mental fixation on reaching the ridge – they were unable to accept Dodge's new tool, the escape fire. It was unfamiliar and didn't fit into their existing expertise and training. So they ignored it and relied on getting to the ridge – a tool still central to their expertise. For most of us, as with the crew, a new tool needs to be introduced not at a time of stress, when we will fail to process its significance, but before.

The importance of examining, evaluating and knowing if and when to drop your tools prior to a stressful period is illustrated in fire service training today[3]. Firefighters are trained to run both with and without their tools, to demonstrate that they can run faster without tools. While this sounds obvious, the training actually embeds this tool in their expertise, and at times of stress they are now equipped to decide whether running or holding onto their tools is better. This is part of the concept of comparison, awareness and refinement. The comparison stage comes by examining how you would perform both with and without your tools (running slow versus running fast), awareness (that you can actually run faster without tools), and refinement (becoming aware of the time when it is correct to shed those tools). This concept is illustrated by Rumsey, who said in the review that followed the tragedy that he thought Dodge had simply gone mad lighting another fire. He pointed out that if it had been explained to him on a blackboard in Missoula prior to the event, he might have been able to process it[6].

However, the difficulties in examining your tools cannot be overstressed. For many of us, using engineering tools is part of who we are, and dropping them is akin to giving up a little of that identity. As Norman Maclean puts it so beautifully in his book on the tragedy, *Young Men and Fire*, "When a firefighter is told to drop his firefighting tools, he is told to forget he is a firefighter and run for his life"[6]. Many engineers, no doubt, would feel a similar dilemma.

Examining our tools

This is not to suggest that we drop our tools across the board and revert to first principles. To suggest so is as ridiculous as suggesting a firefighter should throw away his Pulaski and fight fire barehanded. But there will always be situations when over-reliance on these tools will let us down; when we get to that point, we will need to know their limitations and recognise when to drop them. If not, Mann Gulch tells us we will revert automatically and rely on them regardless of whether it is appropriate to do so.

When we find ourselves in such a situation, will we act like 15 firefighters running uphill, clutching our tools, and heading for a ridge out of reach? Or will we be more like Dodge? Will we know our tools well enough, as individuals, to identify when they are no longer useful and drop them, instead lighting an escape fire? Will we think like an engineer, the way we're meant to?

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