Chapter 5  Safety and Damage

Poison is in everything, and no thing is without poison. The dosage makes it either a poison or a remedy.

Paracelsus, physician and botanist (1493–1541)

Proportionate effects

We appear to live in a causal world where what happens next is determined by what is happening now. This relationship of cause and effect is easiest to follow if each element of the cause determines its own part of the effect. Such a relation between cause and effect is called linear in mathematical physics. In fact, linearity is really a rather basic and simple idea that does not require fancy mathematics to appreciate.

Here is a simple example. If you are selling me apples and pears, the amount of money that I hand over depends on the number of apples and pears that I buy. Normally, the amount of money that you charge me will simply equal the number of pears times the cost per pear, plus the number of apples times the cost per apple. That is linear – the cost of an extra apple does not depend on the number that I have already bought, or on the number of pears. But it could be otherwise. You could say that extra apples after the first dozen are half price, or that pears are more expensive unless I buy apples too – or that you will pay me to take the first dozen pears, but then charge for further ones. Such pricing is non-linear, and modern supermarkets have certainly learned how to use it to encourage us to buy!

The standard test of linearity is the Superposition Principle. If the total cost is the same as the sum of the cost of buying each apple and pear separately, the pricing is linear. It is true that, if linearity applies, a graph of cost against the number of apples is a straight line – but the reverse is not true. If the slope of the graph for apples changes depending on the number of pears, the pricing is non-linear.
Many aspects of the world described by modern physics are linear or nearly so. Indeed the scientific method is most useful if we can disassemble a problem into pieces and then add the contributions of each back together and still have the right answer. This is the feature that makes telecommunications and audio systems valuable – linearity makes it possible to work backwards and reconstruct the input signals from the output – for example, to hear the strings as separate from the wind instruments when listening to a piece of music. It is linearity that makes it possible to solve problems in quantum mechanics, and that allows light waves and radio-waves to cross through one another without any effect. If what is transmitted on one TV station affected what was received on all the others, that would be non-linear – and not much use either! Similarly, if what we see when we look at one object was influenced to some extent by light from objects that we are not looking at, that would be non-linear too. Fortunately that is not the case for light and electromagnetism. A linear world is like a world of LEGO®, easy to work with scientifically because it is built up of separate bricks.

But not all causes generate effects independently in a linear fashion. Take social behaviour, for instance. The way in which people interact one-to-one gives no information on how they behave as a crowd. So, for example, most aspects of economics are non-linear. Non-linearity occurs in physics too, most obviously in the turbulent flow of fluids.

On page 44 we explained how the relationship between radiation dose and clinical damage has been assumed to be linear – the LNT model. So the question is whether this linear assumption is correct, or not. It will be seen later, that some data fit with the Superposition Principle and some do not, but that linearity is not what we should expect from an understanding of modern biology. The science is about understanding what is occurring at

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19 Much use is made of approximations and changes of mathematical perspective in the description of modern physics, all with the aim of making problems linear, since then they are far easier to solve and understand.
the biological level, not about fitting straight lines to data, or even curves. There was a similar situation in early planetary science. The real reason for discarding Earth-centric cosmology in favour of the Copernican theory was simplicity – the Earth-centric cosmology may have contrived to fit the data, but its calculations lacked simple explanation.

Analysing non-linear systems is possible but not as simple as linear ones. To go back to the apples and pears – if I have accepted your offer of Buy one get one free or One pound off apples when you buy pears, I may be content with my purchase, but I cannot say how much the apples cost me because the question does not have a simple answer.

Linearity is about independent causes. The superposition test asks two questions. If the response to cause $A$ is $\alpha$ and the response to cause $B$ is $\beta$, is the response to $2A$ just $2\alpha$; and is the response to $A$ and $B$ together just $\alpha+\beta$? If either of these is untrue, the response is non-linear. We already had an example on page 35 – the response to different volumes of music. It can be dangerous to impress linearity on our view of a problem, just because it makes the assessment easier. A more pragmatic view is suggested by the words of Paracelsus in the early 16th century quoted at the start of the chapter. He understood that the hazard – or benefit – associated with any given action or dosage is often non-linear. Whether administering a drug at a certain dose level is beneficial or harmful is a matter for experimental evidence. In popular parlance we say you can have too much of a good thing. Looking at the same situation from the other end, it may be that a little of a bad thing will do no harm, and may even do some good.

**Balancing risks**

Life presents choices, whether to individuals or to society as a whole. Any choice carries a certain risk and these have to be balanced. Two of these choices involving ionising radiation are illustrated in Figure 6. When a malignant tumour is diagnosed a patient must choose between the likely course of the cancer and a
dose of radiotherapy with its radiation side effects (if not a different treatment). Medical advice may guide but there may be mortal dangers either way. Nevertheless, a decision in favour of radiotherapy often results in an extension of enjoyable life, in spite of the high doses that treatment involves. This is a decision for the individual.

Figure 6  Choices involving ionising radiation. (a) Balancing risk between the effects of radiotherapy and cancer. (b) Balancing risk between nuclear waste and carbon dioxide emission.

An equally significant choice faces society collectively – whether to minimise the impact of climate change by opting for nuclear power with its attendant waste and perceived radiation risk – or to avoid any effect of radiation while incurring
significant greenhouse gas emission. Although the choice is popularly supposed to be equivocal and shrouded by uncertainty, the dangers of ionising radiation are well studied and most of the facts are known. Climate change is a newer problem and there are some aspects to be clarified. But the main elements are understood and decisions have to be made – there is no longer any time to waste. Mankind, the patient, must make the decision.

In classical times the Romans drained swamps and reduced malaria in Italy without knowing the role played by mosquitoes. Similarly, the Victorians who had little understanding of epidemiology built public sewers and fresh water supplies in London. They took firm decisions that controlled the transmission of typhoid, and other diseases, without knowledge of exactly how that control was effected. But we know more about the effects of radioactive contamination and ionising radiation on life than the Victorians did about water-borne diseases.

These are not personal decisions – both climate change and the risks of contamination and radiation exposure affect the population at large. When dangers to others are at stake, it is normal to take a more conservative view of risk than when the hazards are purely personal. But where the choice is between two public global risks, such reticence is misplaced – any degree of precaution should be applied equally to both. Whether a conservative or radical line is taken, the need is to choose the least risky alternative. That is the only question. The answer is not given by appealing for caution in the name of a precautionary principle.

In some countries politicians tentatively support a pro-nuclear power policy; but in others nuclear power is still excluded politically, or even outlawed. Everywhere, leaders and investors need to know whether the public supports decisions in favour of nuclear power. They cannot instruct the court of public opinion – they need the backing of a significant number of people who have read the evidence, questioned it themselves and taken their own view. The following chapters provide evidence to that end.
The comparison to make is that between the combustion of fossil fuel and nuclear fission, as the means of large-scale energy production. Both involve chain reaction processes and so both can be dangerous if not controlled with care. Both produce waste products that need to be managed. But because the chemical energy released in combustion is on a scale some five million times smaller than nuclear energy, the quantity of fuel needed for the same delivered energy is some five million times greater – and so too is the amount of waste generated. In the fossil fuel case, all of the waste is discharged into the atmosphere. In the nuclear case, all of the waste is captured. Since it is largely composed of heavy non-volatile material, it can be safely buried deep in the Earth's crust where it will stay put for many millions of years as in the case of the Oklo Reactor [6, 7]. People have worries about the radiation, the contamination and the cancer, that such waste might cause. In the next two chapters the best world evidence will be used to look carefully at these questions. But first we look more broadly at how we are protected against dangers of all kinds.

**Protection of man**

At the most basic level man is protected by the provisions of evolutionary biology. These give an extraordinary degree of defence against any agent that interferes at the microscopic level, and human beings are usually quite unaware that this is happening. Many elements of such protection turn out to be general and are not specific to one particular type of threat.

Like other higher animals, man is also protected at a second level by the effect of learned habits and rules, passed down by instruction from one generation to the next. With these we include the laws and regulations to which society assents. This level of protection is passively learnt and followed, but not necessarily understood.

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20 Unless it is captured, a desirable but technically unrealistic task on the scale required.
But, uniquely among creatures, man can also protect himself by fast rational decision-making, based on observation and understanding – that is by judgement, scientific or otherwise. And it is the business of education to hand this faculty of judgement down to later generations. This education is not concerned with learning facts by rote, or with copying from others, but with understanding and the realisation of new solutions.\footnote{Unfortunately, education is often presented in the media as the ability to recall facts. But the Web is best at that, and education should concentrate on understanding.} It permits man to adapt to his environment far more rapidly than other animals.

When Charles Darwin published \textit{The Origin of the Species} in 1859 he showed how life on Earth has developed and how species have evolved to cope with the stresses of their environment. The reactions of living organisms to stress are optimised through natural selection – survival is only for those able to protect themselves. The design may not be purposeful, but it is effective nevertheless. However, it is wasteful when there is a change in the pattern of stress – many individuals may perish in the process of selecting the variant that responds in the way best suited to survival. The species may survive, but individuals do not. The selection process may take many generations, and so it is beneficial if generations are short-lived. Otherwise the response would be slower and less effective in the face of stresses that change rapidly.

Today Darwin's ideas are understood to work at the cellular level as well as at the level of whole organisms. Because the turnover through the cell replacement cycle is much faster, an immune reaction to threats at the cellular level can provide rapid protection against disease and infection. But not all threats come at that level.

Through passive learning, animals teach their progeny how to cope with dangers. The polar bear guides her cubs and plays with them in pretended fights. Mock battles and sibling rivalries
between children are rehearsals for later life, when judging the reactions of others becomes all important. Magic and simple deception are essential to children's theatre. Every child in the audience shouts out *He's behind you!* as he sees the villain creeping up behind the actor on the stage. The apprehension and excitement arise from the interplay of fear and knowledge that children feel from an early age. They learn, not to hide from the drama on stage, but to watch and warn or take action, uncomfortable though that may be. Their ability to survive in life will depend on the extent to which they can balance these influences. Much of their play and entertainment is designed to teach them to cope with their imagination of the unseen.

The children's reaction in pantomime highlights that the greatest dangers in life may be the ones that we cannot actually see. In principle, dangers that are seen may be sized up and avoided. Unseen dangers can only be imagined, and, if imagination runs away with itself, confidence and trust collapse and we may end up spooked by things that are actually beneficial. Imagination is a loose cannon – fired without aim, it can destroy that which it seeks to defend. The task is therefore to understand what we cannot see and, at the same time, to control our imagination.

Simple education, with its emphasis on tradition and collective rules that follow the consensus view, does not provide the best guidance, especially when conditions change. The individual with his ability to imagine and think for himself pro-actively is essential. Hans Christian Andersen's tale of *The Emperor's New Clothes* teaches children – and everyone else – the vital lesson, that they should learn to trust the evidence of their own eyes and listen to their own judgement, rather than what they are told. While the vain Emperor with his sycophantic courtiers accepts the majority view that he is wearing a magnificent suit of new clothes, a small boy in the crowd shouts out that he is not wearing any clothes at all. So an important aim of education should be to encourage everyone to challenge accepted opinion.

Man can do better than other creatures. He can use his knowledge and understanding of science to study quite new
hazards and work out completely new courses of action, all within a generation – a quicker and less wasteful process than macroscopic evolution. For this, a short generational period is no longer an advantage. A longer lifespan, beginning with an extended period of education is better. It maximises the transmission of wisdom and scientific understanding to younger members of society. For whatever reason, this is the way in which man has been changing in recent centuries, longer lifespan and slower generational turnover. With education, individuals, as well as the species, can respond quickly to a changing environment. Whether mankind as a whole can change his way of life fast enough to respond to climate change remains to be seen.

**Damage and stress**

Does the chance of damage depend linearly on stress? This is a general question, and it is a good idea to have a look at other instances, before getting to the particular case of the stress that comes from a dose of ionising radiation.

We may think first of a purely mechanical case, like a bridge – how does the survival of a bridge depend on the stresses put upon it? The stresses might come from the traffic crossing it and from the wind and weather buffeting it. If the bridge is designed and maintained properly, when the wind stresses it a little, it will flex a little, but when the wind stops blowing it will spring back to its initial shape so that there is no lasting damage – this is called an elastic response. The temporary flexing is in proportion to the stress, and such a linear mechanical response was first described by Robert Hooke in the 17th century and is known as Hooke's Law.

But that is not the whole story, for if the wind blew very much harder, the bridge might be damaged – that is metal might be permanently twisted, cables snapped or support piers cracked. Then the bridge would not completely recover when the wind ceased and the damage would remain unless repaired. A simple graph can be used to show the damage for a particular stress.
Such a curve is called a stress-damage curve or a stress-response curve. In the case of the bridge it might follow a curve like Figure 7b. At low wind strength (stress) there is no permanent movement (damage), as shown by the first flat part, labelled recovery. But for wind strengths above the point labelled threshold, the steeply rising section of curve means that permanent damage increases rapidly until, beyond a certain wind strength, the bridge is destroyed.

It is the business of the engineer to design the bridge so that the threshold is high enough that damage will not occur within the range of predicted wind strengths. He may not have complete knowledge of all the information that he needs, in particular about the wind strength to be expected, but he will include a safety factor in his design, perhaps a factor of three or four. However, to allow a large factor would probably not be affordable, and he needs to balance any extra cost against the reduced risk, for in the practical world there is no such sanctuary as absolute safety at finite cost.

Of course, it is possible that the bridge has no spring back and never recovers when deflected. Then the stress-damage curve would follow a straight line similar to Figure 7a (presumably with some limit corresponding to complete failure). Such a
dependence of damage on stress is called linear no-threshold behaviour (LNT). But it is a matter of observation that this is not often the case for a bridge, or any other structure. The non-linear S-shape\textsuperscript{22} behaviour (Figure 7b) rather than the simple linearity (Figure 7a) is essential to the safety and survival of the bridge.

In other examples the recovery region of the stress-damage curve involves explicit repair – a process that takes a certain time, the repair time. Take the effect of laceration and bruising, for instance. This sort of physical damage to the body usually heals in a few weeks. More serious laceration may leave scar tissue – even if the body apparently recovers its full range of functions, the scar tissue may persist, and in later life become a source of medical complaint. In an extreme case of laceration there may be permanent loss of function, or even death. This stress-damage dependence has similar features to that of the bridge (Figure 7b) – a range with no long-term damage and complete recovery, a range where some long-term damage occurs, and a range where permanent loss of function ensues.

**Time to repair**

Repair takes a certain time and any further stress, incurred before the repair is completed, adds to the risk of passing the threshold of permanent damage. Conversely, any biological damage described by LNT would suggest an absence of any repair mechanism – and a failure of biological development to evolve such protection. In biology this is very unlikely and, unless both data and evolutionary circumstances unambiguously indicate otherwise, it is unreasonable to assume that LNT applies.

For a non-linear response the important questions are: Is the shape of the curve as sketched in Figure 7b, as expected through repair or feedback?\textsuperscript{23} How long is the repair time? And what is

\textsuperscript{22} This shape is sometimes described as sigmoid, rather than S-shaped.

\textsuperscript{23} It is sometimes supposed that, if it is not linear, it should be assumed to be quadratic, or linear + quadratic, instead. There is no reason for such an assumption.
the threshold for lasting damage? For the bridge, the repair might be the effect of an explicit maintenance schedule. A bridge that is inspected and repaired regularly is liable to suffer permanently, only if the integrated effect of damage between inspections exceeds a threshold. Repair would make good any damage – re-mortar the bricks, replace bent struts and protect from the elements with a new coat of paint, before the next major storm. Such a bridge will continue in service for a long time if the maintenance schedule is of adequate frequency. This is the way in which machinery and structures are usually kept serviceable and safe. The bridge only suffers permanent damage, if the stresses within a maintenance period accumulate elements of minor unrepai red damage, that together exceed the critical threshold.

There is no fancy technology here – just old-fashioned common sense. But when looked at in the right way, this is often true. From a safety point of view the design of the bridge and its maintenance procedure form a single system, characterised by a repair time and a net damage threshold. Stresses accumulated within the repair time contribute to passing the threshold of permanent damage; but stresses separated by longer periods do not accumulate because repair is effected in between.

**Collective dose**

Suppose that a group of people is subjected to a stress of a kind to which LNT does apply. If $K$ is the slope of the line in Figure 7a, then the damage to each individual would be $K$ times stress suffered by each. By addition, the total damage suffered by the group would be directly determined by the sum of their individual stresses with the same slope $K$. Since what is of interest is the combined risk to the group, it would be simplest just to measure the sum of stresses – this is called the collective dose. The damage is then found by multiplying this by $K$. This mathematical result is particularly simple, and it is rather neat and easy to work with. From a regulatory position all that is
needed is to add up the total collective dose and multiply by $K$ – and there you have the collective damage, or risk assessment.

In particular, for radiation the collective dose can be calculated in this way – simply add each equivalent dose measured in sievert for all those individuals involved. This prescription is set out by the International Atomic Energy Agency (IAEA) [8 p.24] to be a self-evident basic method:

*The total impact of the radiation exposure due to a given practice or source depends on the number of individuals exposed and on the doses they receive. The collective dose, defined as the summation of the products of the mean dose in the various groups of exposed people and the number of individuals in each group, may therefore be used to characterize the radiation impact of a practice or source. The unit of collective dose is the man-sievert (man-Sv).* [underlined emphasis added]

[Note added in proof: It may be significant that this webpage was removed from the IAEA website at some time between 10 February and 17 April 2009. Perhaps the IAEA no longer consider it self-evident, or true.]

But is the total damage (or detriment) related to the collective dose determined in this way? The conclusion drawn in the second sentence quoted above does not follow if the reaction of living tissue to radiation is not linear. Then the use of the collective dose would not be applicable – and its use would give quite wrong answers. In the next chapter we shall see whether this is the case, but first, we look at some other general examples, some for which collective dose is relevant and others for which it is not.

A goldsmith might be concerned at the financial loss due to filings and polishings of metal that get thrown out when they are swept up with the dust on his shop floor. He assesses the metal lost, big and small, adds it up (the collective dose) and multiplies by the price of gold ($K$), and he has a good figure for the related financial loss. In this example LNT applies, for there is no regeneration mechanism for the lost gold.
However, the use of collective dose gives the wrong answer if there is a repair process making LNT inapplicable. Then the compilation of a collective dose would be dangerous in the sense that it would encourage a total risk assessment that is significantly in error. How about the risk incurred by humans through blood loss? Like gold, blood is highly valued. Since the body of any adult contains about 5 litres of blood, a loss of this much at one time by one person would be fatal. If a group of people suffer blood loss in an accident, it is true that the more people there are in the group, and the more blood that each loses, the more serious would be the accident. It is tempting to quantify this by adding up the total blood loss, the collective dose (in man-litres). If LNT applied, the gravity of an incident would be determined by this collective dose. Since the loss of 5 litres by an individual is fatal, the effective number of fatalities arising from the incident would simply be the volume of lost blood in litres divided by 5, the number of man-litres corresponding to one death. If that were true, then every 10 donors visiting a blood clinic to donate half a litre of blood would incur one fatality!

Why does the use of collective dose with an LNT assessment give a nonsense answer in this case? The crucial point is that over a period of time a healthy individual makes good any loss of blood – so the loss is repaired. The use of the collective dose ignores this. Each adult can lose half a litre of blood and it will be replaced within a few weeks, with no risk whatsoever. So the loss of 100 litres of blood by 200 people happens in a successful blood donor clinic. The loss of 100 litres by 50 people over a year gives no ill effects either, although lost by 20 people over a short period might cause fatalities. We see that an assessment of risk using collective dose can lead to absurd conclusions, if there is repair and, therefore, non-linearity. And the erroneous analysis is not corrected by fiddling with mathematics, such as using a quadratic dependence on collective dose. The repair mechanism simply invalidates the use of the collective dose.

Doses (or stresses) may be either acute or chronic. If the response to a single acute dose is known and the repair time is
known, a reasonable assessment of the effect of a regularly repeated or chronic dose can be made. In the case of blood donation this was assumed above – a donation of half a litre every few months creates no hazard. However, any extra blood donations within one repair time would have a cumulative effect. Generally, this means that, if the threshold of damage due to a single acute dose is $A$, then the threshold of damage due to a chronic or repeated dose rate is $A/T$, where $T$ is the repair time.

The shorter the repair time, the higher is the threshold for damage due to a chronic dose rate. Reality may be a little more complicated – there may be more than one repair process and more than one time.

**Safety margins**

The safety margin incorporated in the design of an affordable structure like a bridge might be a factor of four, say, and it seems that nature also employs modest margins. For example, in the case of blood loss by an individual, the margin is 10 between the safe stress of a half litre loss and the fatal stress of a 5 litre loss.

Another example is the risk caused by fluctuations in body temperature. These are normally stabilised by balancing metabolic activity with the cooling effects of blood circulation and perspiration. Variations associated with intense exercise or a light fever amount to a degree or so and cause no lasting damage. But changes of two degrees or more in tissue temperature are potentially serious, and after a high fever a period of rest is often prescribed. At the other extreme, a temperature excursion of 20 degrees or more can cause cells to melt and cease to function. Leaving aside the details, a variety of feedback mechanisms is seen to stabilise temperature, again with a safety factor of a few between the onset of damage and a fatal condition.

None of these factors is precisely defined, of course, but they fall in the same range. The point is that the use of a much higher safety margin would be wasteful of resources, in biology as in the engineering of a bridge. Nature is a master at balancing risks against resource costs, and mankind would do well to study her
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example. So what safety margin is affordable in connection with ionising radiation? We shall consider the question in later chapters.

**Multiple causes**

It is common experience that a patient, whose health is poor on account of one stress, is likely to be adversely affected by a second imposed at the same time – more likely anyway than by the two stresses acting separately at different times. If the response were linear this would not be the case – the effect of the stresses would simply add. Indeed, the collective prognosis would be the same, even if the stresses were experienced by different people! But this is not so because the response is non-linear. In the language of the analogy of the apples and pears, the price of an apple is different if you have bought a pear.

It has been found that the combined mortality due to malaria and AIDS exceeds the sum of each separately [9]. This is a failure of linearity and has important implications for world health. Malaria and AIDS are unrelated, but they both load the immune system, which has some threshold for failure. But we do not need to understand the mechanism to appreciate this. This is simply the effect of non-linearity. The mortality due to AIDS and due to malaria cannot be unscrambled, just as the pricing of apples and pears could not be unscrambled when the pricing was non-linear.

In normal health care, following an incident of excessive stress, the treatment of a patient usually calls for a period of convalescence, completely removed from sources of further stress. Typically the duration of such recuperation is about a week or so in simple cases. As a result of this period of inactivity, risk of long-term damage is minimised, and later the usual pattern of stress may be re-imposed with full functionality. So here is a measure of a typical clinical repair time. This is familiar common sense, not new science. But it is not compatible with LNT.
With advancing age the threshold of damage for most stresses becomes lower, whether from the accumulated effect of scar tissue or from a general loss of protective immunity. The rapid repair processes due to cell replacement and the quick convalescence of youth become slower.

**Beneficial and adaptive effects**

To speak of stress suggests that the response is always negative. This may not be the case, as Paracelsus remarked. A dose of a drug may have a beneficial effect or a harmful one, depending on the dose.

![Figure 8](#)  
**Figure 8** Sketches of the dependence of damage on dose, (a) where a low dose is beneficial, and (b) where the response is adaptive with the threshold increased by a history of previous doses.

The effect of the drug paracetamol provides a trivial but familiar example. One hundred tablets taken at once by a single individual would be fatal. Spread evenly among fifty patients, they would not be the cause of any death, but might have a positive impact on health. Such non-linearity is a normal feature of toxicology. For instance the dose-damage curve might be as sketched in Figure 8a. Over a certain range of dose the damage is negative, that is to say the drug is beneficial. But for a greater dose it may be harmful, or even fatal.
The process of evolution does not simply determine an unchanging stress-damage response curve. It also provides an ability to track the pattern of past stresses so that the response curve itself changes. For example, the dose-response relationship may depend on the pattern of earlier stresses, as suggested by the qualitative sketch, Figure 8b. The administration of low doses may develop an ability to tolerate higher doses. Such a pattern was first seen in the extraordinary discovery by Edward Jenner in 1796 that giving a mild dose of disease (cowpox) to a patient provides greatly enhanced protection against a more virulent strain (smallpox). The study of this effect is the science of immunology. It can provide fast adaption for the individual by selection dynamics at the cellular level. In such cases the individual is quite unaware that he is receiving this protection.

But there is a further kind of rapid adaption that is not at the cellular level and is conscious. This may be illustrated by returning to the example of the bridge. What happens when a bridge fails? In a non-cognitive world engineers might simply select, without thinking, a design of replacement bridge by copying one of those that happened to remain standing at the time. The response time, the time for bridges to be re-designed for a changing environment, would be long and characterised by the natural life of a bridge. But that is not what happens in the modern world of man. Following the failure of a bridge an enquiry is held. The reaction to the collapse of the Interstate-35 bridge in Minneapolis on 1 August 2007 provides an apt example. Within 24 hours all aspects of the design that failed were under consideration [10]. Design modifications were put in hand, maintenance and inspection procedures reconsidered, models built and tested, and all lessons learnt applied to other bridges of similar design. This is a proactive cognitive process made possible by intelligence. Then the survival prospects for all such bridges benefit from the fast adaptive response.

Many creatures engage in some kind of education, for only those species that pass on beneficial habits to their young enjoy enhanced survival characteristics. But such education by
tradition and rote is slow to change, and a short life and generation gap are necessary to speed the reaction to change. Rapid cognitive adaption based on understanding is quite different – it needs a much longer and intensive period of education, and so is best suited to a long lifespan with slow generational turnover. It characterises a proper university education where students are taught to think for themselves, rather than simply to regurgitate facts and formulae as they may have been taught at school.

Adaptive behaviour reduces risks, and examples may be found in quite diverse organisational structures. For example, during the troubles in Northern Ireland in the 1970s and 1980s there were many hospital casualties requiring serious plastic surgery, and the surgical teams there developed exceptional skills. Consequently, anyone else needing plastic surgery at the time was well advised to go to Northern Ireland for treatment. Of course, this just underlines the efficacy of genuine training for any demanding activity. Children need to practise crossing the road. Drivers need to learn how to coordinate the ability to think with the timing and judgement required when driving a car. Practice and experience of the stress involved are necessary for safety, but the essential step in such training is thinking.

Humans have this superior ability to survive. The new danger of climate change is a pressing problem in response to which we need to adapt our way of life. This involves reaching a balanced assessment of all related dangers and keeping a sharp lookout for any sign that our current assessment of any such danger may have been misjudged, for instance the effect of radiation on life.

**Surprise at Chernobyl**

On 26 April 1986 reactor number four at the Chernobyl nuclear power station in the Ukraine exploded. How this happened is now well understood, as described in the international reports by the Organisation for Economic Cooperation and Development (OECD/NEA) [11], the International Atomic Energy Authority (IAEA) [12] and the World Health Organisation (WHO) [13].
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The Russian-built reactor had poor stability and lacked any kind of safety containment vessel. It was in the control of an inexperienced team who did not understand the consequences of the dangerous tests that they decided to undertake. The resulting power surge caused an excess pressure of superheated steam within the water-cooled reactor which blew the top off the structure. Further chemical explosions and fire followed the exposure of the reactor core to the environment. Because of the excessively high temperature some of the core material rose into the upper atmosphere where it was transported over long distances. This included all of the volatile radioactive iodine and much of the lighter fission products. The less volatile heavy elements, such as uranium and plutonium, remained within the reactor or were scattered within shorter distances.

The accident was made worse by the failure of the Soviet administration to cope with the situation as it developed. It tried to hide the news on the international front. Locally it failed immediately to provide iodine tablets and give out the public information required. Later it over-reacted, forcibly relocating 116,000 of the local population without warning, so causing panic and social dislocation. It is probable that this caused more damage to life than the radiation itself. The incident can be seen as one of the elements that lead to the socio-economic collapse of the whole Soviet Empire.

Meanwhile at Chernobyl, an exclusion zone was established around the site. International programmes were undertaken in an attempt to bury radioactive material to keep it out of the natural food chain and major water courses. After the evacuation only those employed in the clean-up programme were supposed to enter the exclusion zone, and the authorities strove to attract further international funds to spend on the reactor and surrounding site. This worldwide attention secured some welcome resources for a depressed region – it was not in anyone's interest there to make less of the accident and its consequences. It followed the story of the failure of the reactor at
Three Mile Island\(^{24}\) in 1979 and the world press accepted the Chernobyl story as confirming a general distrust of nuclear safety. Early international reports sought to record the facts about the radiation and the spread of contamination, but did not attempt to question the overall risks to human health. In this way security and resources were maximised for a situation in which panic and social dislocation were manifest.

But in recent years those who have visited the site have reported surprise. Instead of the wasteland they had expected, they found that wildlife is surviving, and in some cases thriving, in spite of the radiation levels. An American reporter, Mary Mycio [14], originally from Ukraine, has spent much time there and written eloquently of the flora and fauna that she found. A BBC documentary [15] on Chernobyl was shown in July 2006 with similar conclusions. An excerpt recorded:

> Yesterday we spoke to an expert on the wildlife of the Chernobyl zone, who surprised us by saying that animals did not seem to be too bothered by the present level of radiation. He said he had searched for rodents in the sarcophagus, and had not found any – but he put this down to the absence of food rather than the presence of the reactor's highly radioactive remains. Birds nested inside the sarcophagus, he said, and did not appear to suffer any adverse effects.

These observations raise a simple question, is there something wrong with the accepted orthodox view of the dangers of radiation to life? Evidently the animals, birds and plants in their habitat at Chernobyl are radioactive, as anticipated. Yet, in some cases at least, they are no worse off now with the radioactivity but without human settlements than they were previously with human habitation but no radiation. Is it true that human habitation is as bad for the environment as a large dose of

\(^{24}\) In the Three Mile Island accident control of the reactor was lost but the containment vessel was not ruptured, there was no loss of life and the release of radioactivity was small.
nuclear contamination? We should question anew many of the old assumptions used in the analysis of the effects of radiation on life. In particular, have we allowed the use of LNT to give unreasonable safety assessments, as would be the case if we were to apply it to the dangers of blood loss? Having opened the question with these non-scientific observations, we should examine the data and the science.