DIVIDE & CONQUER

30-second foundation

3-SECOND CORE
Engineers analyse complex systems by dividing them into simpler elements and accounting for influences that cross element boundaries. Computers do most of the calculations.

3-MINUTE IDEA
A complex piping network carrying water is analysed in parts. At each pipe joint, the sum of the separate water flows towards the joint must be zero: water cannot disappear without a leak. The pressure change along the pipe depends on the pipe elevation and flow. We can represent all these relationships with simultaneous equations that a computer can solve. Electrical circuits, factory production lines, city traffic congestion and communication networks can be analysed using similar methods.

Engineers predict the behaviour of systems so complex they can defy human comprehension. They divide complex systems into simpler parts with carefully chosen boundaries and account for the influences that cross boundaries. For instance, when predicting a car's behaviour, engineers draw a 'free body diagram' for each wheel. The diagram excludes everything but the wheel and the forces that act on it. It shows the road force pushing the wheel up. The car's weight, transmitted to the wheel through the axle, acts downwards. The axle driving torque twists the wheel and the road exerts a friction force. The wheel and tyre could be defined separately, and subdivided into many smaller elements, with analysis of each one. Finer subdivision can yield more accuracy, but it takes engineers time to define the element boundaries and forces. Computers handle calculations, but the engineer has to guide element definition and assess the accuracy and reliability of calculated results. Engineers learn appropriate levels of subdivision depending on the accuracy required and the consequences of simplification errors. They use this approach for modelling complex systems, such as the structural stability of an underground mine, rush-hour traffic congestion and radar beam forming.

RELATED TOPICS

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APPLYING MATHEMATICS
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ENGINEERING THINKING
page 26

FORCE EQUILIBRIUM PRINCIPLE
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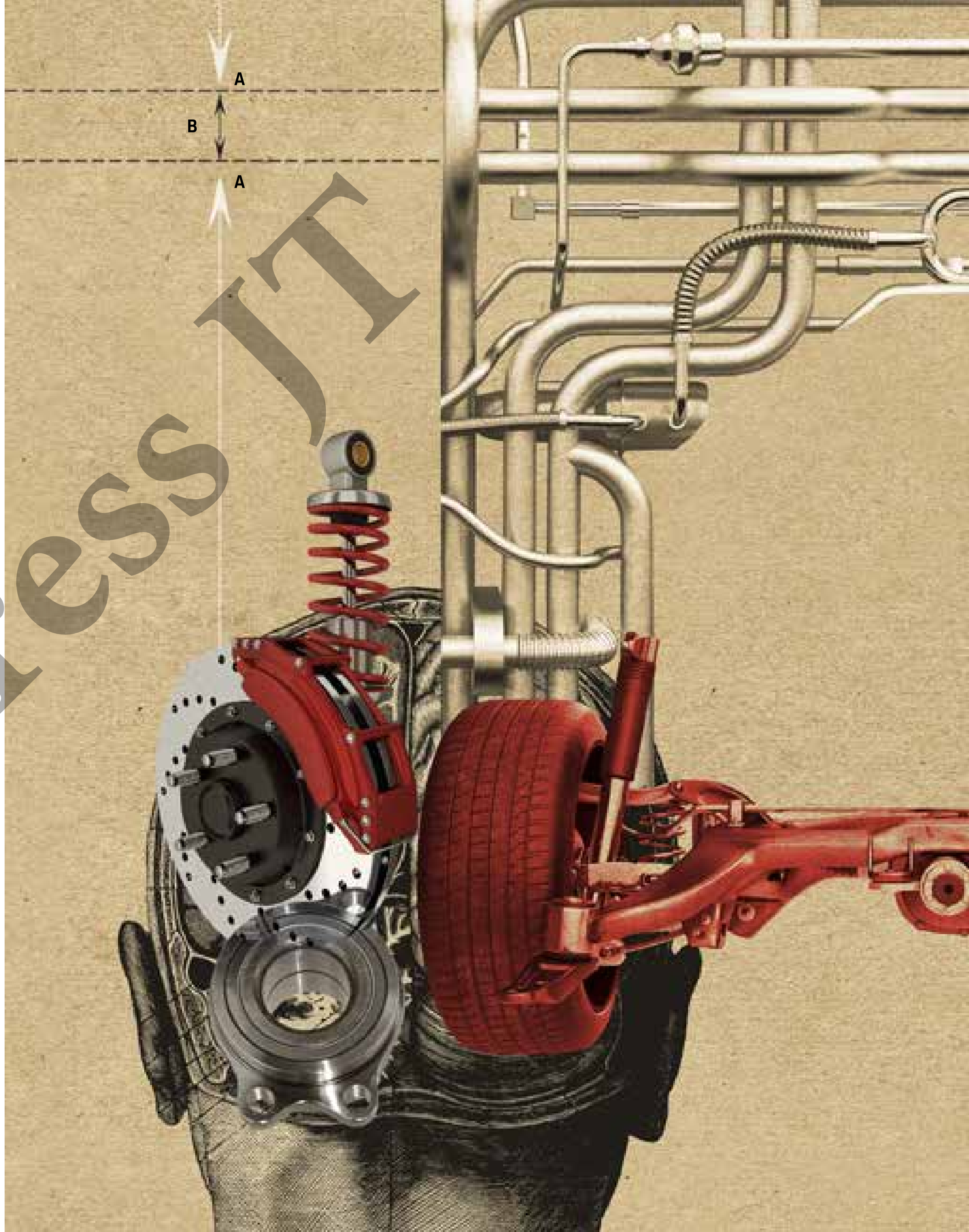
3-SECOND BIOGRAPHIES
CHARLES-AUGUSTIN DE COULOMB
1736–1806
French engineer who described friction, explaining why cars skid during braking, and the electrostatic forces so critical in nanotechnology.

GABRIEL VOISIN
1880–1973
French aviation pioneer who invented the first anti-lock brakes to help prevent skidding.

30-SECOND TEXT
James Trevelyan



Automotive engineers design new cars using components that have proved to be reliable.

CIVIL ENGINEERING

30-second foundation

3-SECOND CORE
Civil engineering enables buildings, roads, bridges and all the other structures in our built environment, ensuring that they are safe and durable enough to last for centuries.

3-MINUTE IDEA
Structural engineering, a part of civil engineering, is about ensuring that buildings, dams and bridges stand up. Calculations based on maths and physics principles predict how structures respond to the forces that nature throws at them – gravity, wind and earthquakes. Equally important, structural engineers predict forces during construction. That's why homes, schools and offices are safe to live in. Spectacular structures such as huge bridges reflect the work of structural engineers, as do invisible structures such as tunnels.

Civil engineering is about roads, railways, buildings, water, sewerage and much more. Civil engineers such as Eugène Belgrand and Joseph Bazalgette created sewer systems in Paris and London, eradicating cholera and saving the lives of millions. The Industrial Revolution reduced the cost of iron and steel in the nineteenth century and Thomas Telford showed how it could be used for bridges, canals and harbours. Together with Isambard Kingdom Brunel's railways, bridges and ships, these developments transformed transport. Today, civil engineers are working to solve challenges and improve people's lives – from creating flood defences and dams to building our largest infrastructures and tallest buildings. Every project poses challenges: there may be obstructions in the ground or poor soil conditions; tunnels or structures that the new construction needs to weave through; or constraints on finance and time. Engineers think creatively to work through these problems, try different solutions and choose the best option. Finding creative economic solutions for difficult construction challenges is immensely rewarding, and civil engineers embrace new technologies to create a world that can support future generations.

RELATED TOPICS
See also
GEOTECHNICAL ENGINEERING
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ENGINEERS & ARCHITECTS
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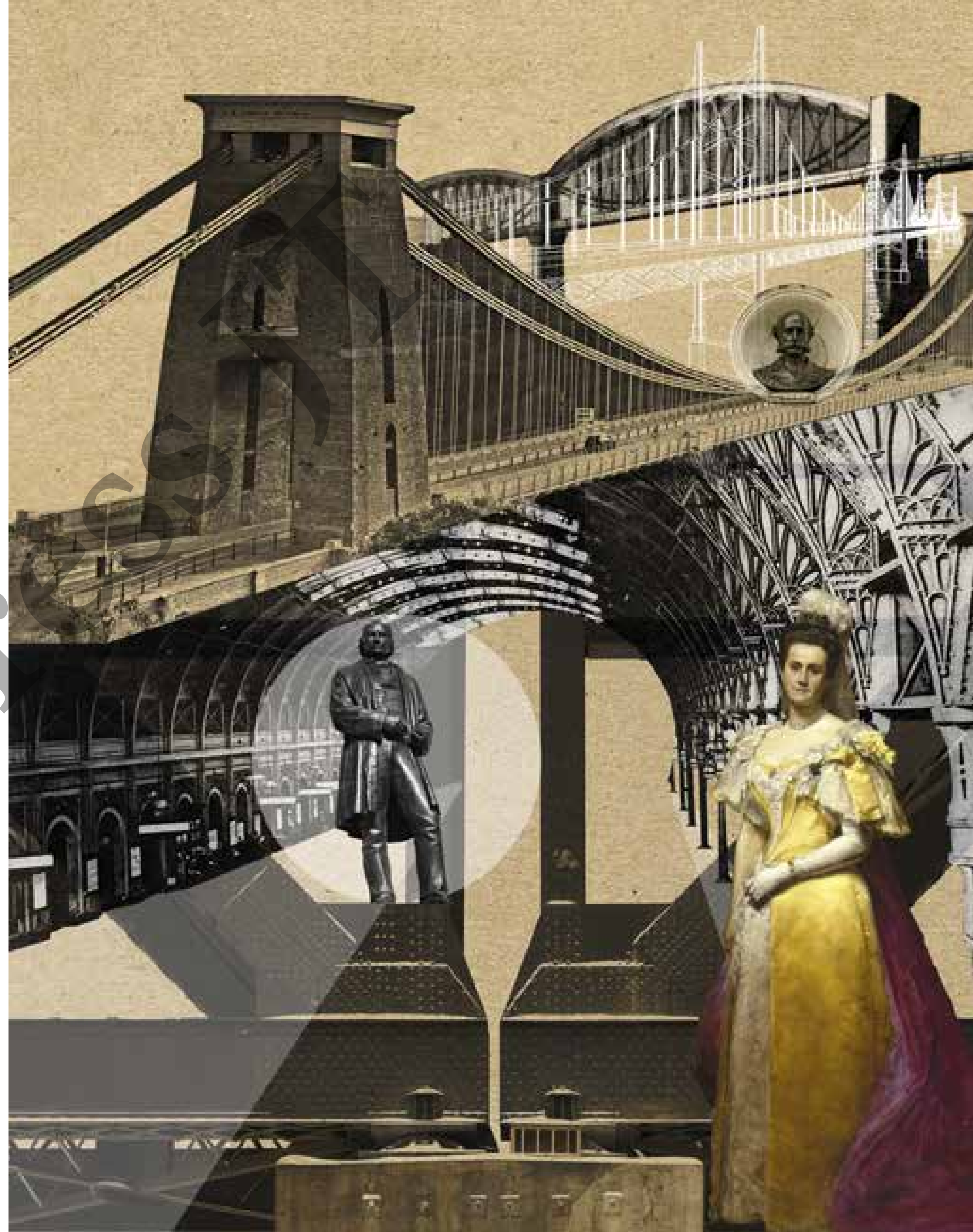
3-SECOND BIOGRAPHIES
SIR MARC ISAMBARD BRUNEL
1769–1849
French-born civil engineer, father of the more famous Isambard; created the 'Thames Tunnel', the first under a navigable river.

EMILY WARREN ROEBLING
1843–1903
Managed the Brooklyn Bridge construction for 11 years, after father-in-law, designer John Roebling, died; learned civil engineering from her incapacitated husband.

30-SECOND TEXT
Roma Agrawal



Civil engineers create the things we take for granted but would find hard to live without.

FAZLUR RAHMAN KHAN

3 April 1929
Born near Dhaka, British India, now Bangladesh

1950
Graduates in Civil Engineering at Dhaka University; appointed assistant engineer, Highway Department

1952
Awarded Fulbright Scholarship and Pakistan Government Scholarship

1955
Completes PhD; employed by Skidmore, Owings and Merrill Architects (SOM), Chicago

1957
Director of Pakistan Building Research Centre, Karachi; Technical Advisor to Karachi Development Authority

1960
Returns to SOM, commences teaching at Illinois Institute of Technology

1963
43-storey DeWitt-Chestnut Apartment Building completed

1966
Appointed partner in Skidmore, Owings and Merrill

1967
Becomes naturalized American citizen

1969
John Hancock Center completed in Chicago, with tubular frame design

1971
Pioneers use of computers for structural calculations and design drawings

1981
Hajj Terminal at King Abdulaziz International Airport receives Agha Khan Award for Architecture

27 March 1982
Dies in Jeddah, Saudi Arabia

Cities have been both the cradle and products of engineering for at least 8,000 years. Skyscrapers form the heart of modern cities because people can live and work close to each other, developing trusting relationships on which engineering, trade and commerce depend. The 'father of tubular designs', Fazlur Rahman Khan, transformed skyscraper design in the 1960s.

Born in Bengal, now Bangladesh, in 1929, Khan graduated in civil engineering from Dhaka University, winning a Fulbright scholarship to study in the US. After completing a PhD in 1955 researching reinforced concrete design, Khan went to work with Chicago architects Skidmore, Owings and Merrill, because they were happy to let him take charge of design and construction projects. The firm was renowned for skyscraper design. Khan soon realized that horizontal live loads from wind and earthquakes pose the greatest design challenges for tall building structures. He explored new ideas, working with students at the Illinois Institute of Technology and through public and professional lectures.

At the time, masonry shear walls between interior steel columns resisted horizontal loads. Buildings had to be rectangular, with little flexibility to change the internal layout. Khan's breakthrough was to design the outer shell of the building as a framed tube to resist horizontal loads, reducing the amount of steel needed by 40 per cent or more. His design eliminated almost all the interior columns and masonry walls, allowing unobstructed internal spaces. His buildings were taller and less expensive, and allowed architects to design almost any shape they wanted.

In 1963, the 43-storey DeWitt-Chestnut Apartment Building in Chicago was completed, the first skyscraper to use the structural tube frame design. The 110-storey Sears Tower, completed in 1973 and also in Chicago, was constructed as a bundle of parallel tube frames – as Khan described it, a group of pencils bundled together with a rubber band. Use of lightweight concrete and high-strength steel enabled buildings such as the 160-storey Burj Khalifa in Dubai – 828 m (2,700 ft) high. Experts consider that the ultimate height using the tube frame design has yet to be reached. Khan also pioneered innovative building forms such as cable-stayed roofs, notably for the immense Hajj Terminal at Jeddah Airport.

Khan was renowned not only for his technical expertise, but also for his humanity and love of art and literature. He epitomizes the US success narrative, a country that has consistently attracted and rewarded hard-working migrants. Khan died of a heart attack, aged 52, while on a trip to Saudi Arabia. His body was returned to the US and was duly buried in Chicago.

James Trevelyan

MECHATRONICS

30-second foundation

By the 1980s, electronics and micro-computers controlled machines such as robots and car engines. Companies soon needed specialist engineers to design electric machines with sensors and connect them with computers. These engineers also wrote software, because they understood details of the machines. First in Japan, later elsewhere, these engineers became known as mechatronic engineers. Mechatronics has enabled the age of smart machines that can adapt their behaviour. A computer ensures that car engines start easily and run smoothly even in the coldest weather and use the least fuel while minimizing exhaust emissions; another computer senses the key approaching and automatically unlocks the door. Feedback control is one of the main principles used in mechatronics. A car's cruise controller adjusts engine power by feeding the speed sensor signal back to the controller: when the car slows, more fuel is supplied, boosting power; if the speed is too fast, it reduces engine power. Many cars now can automatically follow the car in front on a motorway using radar sensors to measure the distance, with automatic braking if needed. Safety and reliability are the main mechatronics challenges. Systems such as anti-lock brakes (ABS) are so reliable that they can be depended on for safety.

3-SECOND CORE
Mechatronics describes systems with mechanical, electrical and electronic devices working together, usually with computers. These systems help to make complex machines safe and extremely reliable.

3-MINUTE IDEA
Spare a thought for the engineers who design and maintain these complex control systems. Designers aim for reliable and safe operation under normal conditions. A design that allows sensors and other parts to be disconnected for repairs and yet still provides complete, constant safety is much more difficult. Software bugs can remain undetected because maintenance is infrequent. Maintenance technicians need to distinguish persistent software faults from random component failures.

RELATED TOPICS
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ROBOTICS & AUTOMATION
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COMPUTER ENGINEERING
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DRIVERLESS CARS
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3-SECOND BIOGRAPHIES
ÁNYOS ISTVÁN JEDLIK
1800–95
Invented practical electric motors in 1828.

ERNST WERNER SIEMENS
1816–92
Developed electric telegraphs and motors, and founded the Siemens company.

ROBERT BOSCH
1861–1942
Created reliable spark plugs for automobiles, introduced eight-hour work days and ensured his company profits benefitted charities.

30-SECOND TEXT
James Trevelyan

Smart machines sense impending faults and alert technicians when your car is serviced.

ORGANIZATIONAL SAFETY

30-second foundation

3-SECOND CORE
Organizational safety requires engineers to be aware about the social factors that keep complex plants safe. High-reliability organizations adopt human behaviour strategies to avoid disasters.

3-MINUTE IDEA
Disasters are rare events, so the enemy of disaster prevention is complacency. It is helpful for engineers who work with complex hazardous systems to maintain an excellent safety imagination, an ability to anticipate a chain of events that could cause a disaster. Good engineers avoid psychological rigidities that make it difficult to see how everyday actions can contribute to disaster. They listen to plant operators and maintainers who can notice early warning signs of impending faults.

Complex nuclear power plants and oil refineries are very reliable, but when they fail, the results can be disastrous for workers, the public, the environment and the corporation. Keeping them safe requires more than technical excellence. Disaster investigations rarely reveal new technical knowledge, but rather highlight how and why existing technical knowledge was not applied. Management systems are procedures and standards that reflect the best way of designing, operating and maintaining hazardous facilities. Formal risk assessment ensures that hazards are identified and risks are mitigated. A systems view of factors causing disasters requires that we look beyond the technology to the people and the organizational environment. Engineers avert disasters by reporting 'near misses' – minor events that might otherwise have led to catastrophes. However, as employees, their choices are influenced by organizational factors, for example who reports to whom and supervisors' key performance indicators. Engineers also have ethical and professional values that help inform their practice, especially when it comes to pushing bad news up through an organization that could help avert catastrophes.

RELATED TOPICS
See also
NUCLEAR POWER
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PROCESS PLANT SAFETY
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FLOATING FACTORIES
page 120

3-SECOND BIOGRAPHIES
KARL WEICK
1936–
Influenced organizational safety with work on high-reliability organizations.

JAMES REASON
1938–
Known for the 'Swiss Cheese' model (how accidents can happen even with robust safety measures in place).

JUDITH HACKETT
1954–
Led developments in health, safety and environmental regulations for chemical industries and process plants.

30-SECOND TEXT
Jan Hayes

Many high-reliability organizations provide helpful models for effective safety.

SOFTWARE ENGINEERING

30-second foundation

3-SECOND CORE

Software engineers create the programs that enable computers to perform useful tasks. Much of the effort goes into creating tests to find programming errors.

3-MINUTE IDEA

Software architecture refers to system design. As with a physical building, there are many different architectural styles with different characteristics, ranging from a single program to multiple separate programs called components or services. Choosing appropriate architecture for particular requirements demands judgement and experience; once programming has started, it can be hard to change. The right architecture can make it easier to allow changes needed late in a project.

Software engineers create, maintain and develop software systems: the instructions and data that enable computers to perform useful tasks. Software systems are diverse, from video games all the way through to surgical robots. Engineers follow the same processes every time, but the emphasis varies according to the importance of ensuring that there are no critical defects. They start with the requirements – what the software must do and how it interacts with people, machines and other systems. They devise tests to verify that the software performs as expected. They construct computer models representing the software so they can predict performance, or prove its logical correctness. Next, engineers interpret requirements to write programs in computer languages. They encode algorithms into the software: known methods for achieving common tasks, such as sorting a list of names into alphabetical order. Computer languages allow programmers to write human-readable instructions which a computer translates for the processor that will run the software. Most software includes a user interface (UI), enabling someone to interact with the system. Engineers rely on software tools, programs that write much of the software automatically. Finally, they perform tests to eliminate mistakes (bugs).

RELATED TOPICS

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COMPUTER ENGINEERING
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INFORMATION & TELECOMS
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DRIVERLESS CARS
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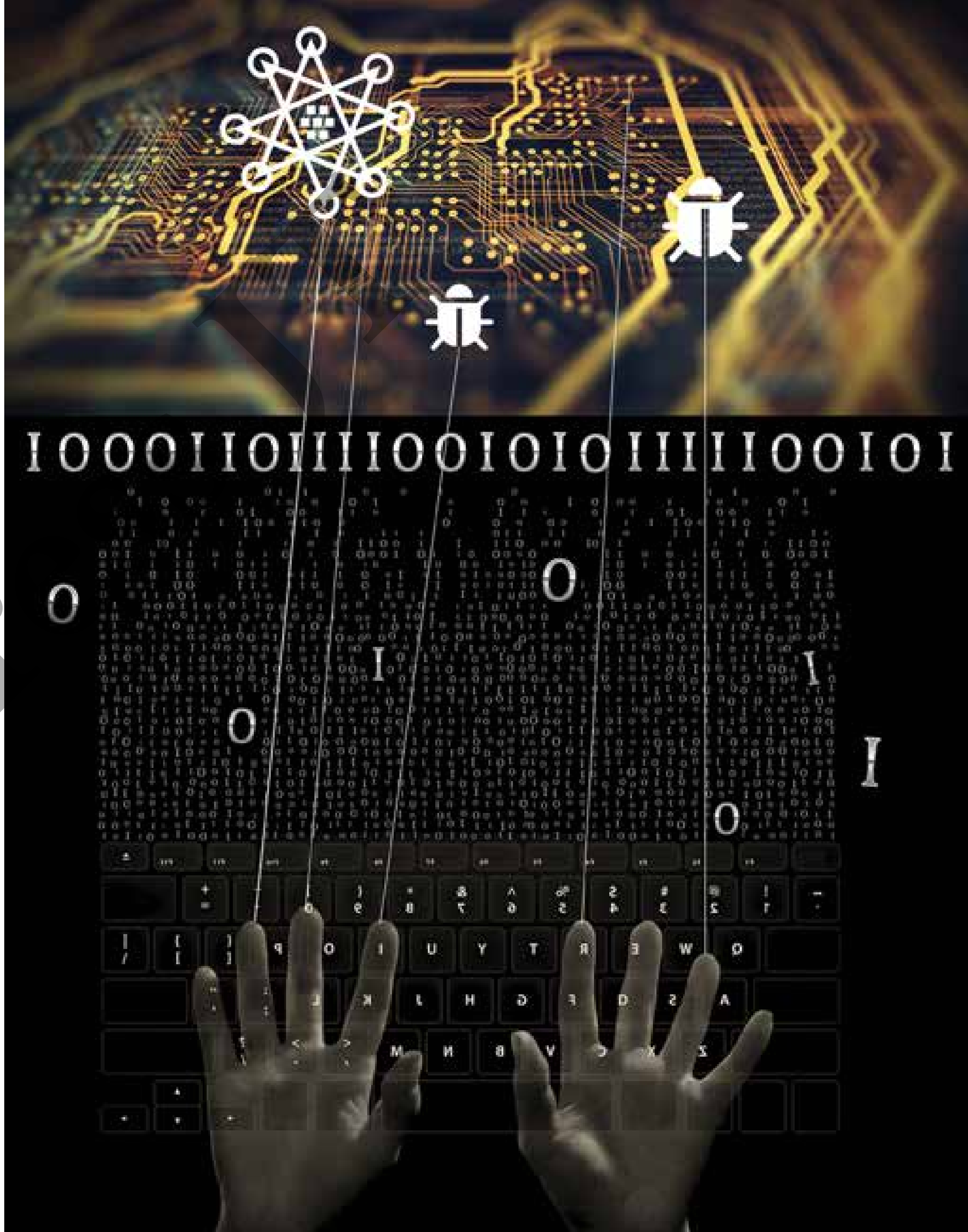
3-SECOND BIOGRAPHIES

ADA LOVELACE
1815–52
English mathematician who recognized that Babbage's mechanical computer, or 'analytical engine', had applications beyond pure calculation, and published the first algorithms.

EDSGER WYBE DIJKSTRA
1930–2002
Dutch computer scientist who formalized many critical ideas in computer science, such as compilers, and helped invent structured programming languages such as Pascal.

30-SECOND TEXT

Andrew McVeigh



Devising tests to detect defects (bugs) takes time, but is critical for good-quality software.

FUNDAMENTALS OF AERODYNAMICS

30-second foundation

3-SECOND CORE
Aerodynamic principles help engineers design aeroplanes, cars, ships and trains, enabling them to predict airflow and the resultant forces. The same principles help explain how birds and insects fly.

3-MINUTE IDEA
Aeroplanes fly because they are able to generate lift from the speed of air flowing over and under the curved wing surfaces. Air moves faster above the wing than below, so pressure is less above the wing, generating an upwards force. Forward motion results from engine thrust or wing movements for birds. Stable flight depends on maintaining correct orientation relative to the airflow. Today, computers help pilots control planes for added safety and reliability.

Aerodynamics began with Leonardo da Vinci's 'ornithopter' invention in 1485. However, achieving sustained flight of heavier-than-air machines took until 1903, when the Wright brothers made their first flight near Kitty Hawk, North Carolina. Aerodynamics explains how fluids such as air move around objects, at least approximately. It explains aircraft flight, as well as trailer trucks, race cars, hydrofoil racing boats and even curved baseball throws. By using aerodynamics, engineers can calculate forces and moments on the object from the flow field: the pattern of fluid motion. Flow fields describe velocity, pressure, density and temperature, which vary with position and time, and also depend on properties such as shape and fluid viscosity. Flow fields can be measured in wind tunnels or computed from equations derived from knowing that mass, momentum and energy have to be conserved. For flight, the four key forces are lift, drag, thrust and weight. Lift and drag arise from the flow field. Lift has to overcome weight for an aeroplane to fly, and thrust from engines has to overcome aerodynamic drag, which tends to slow the plane. Smaller forces from elevators and a rudder stabilize aeroplane orientation and provide turns when needed.

RELATED TOPICS
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MECHANICAL ENGINEERING
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AEROSPACE MATERIALS
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LESSONS FROM SPACE
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3-SECOND BIOGRAPHIES
LEONHARD EULER
1707–93
Laid many foundations for modern mathematics and aerodynamics.

WILBUR & ORVILLE WRIGHT
1867–1912 & 1871–1948
Pioneers credited with inventing, building and flying the world's first successful aeroplane.

ANDREI TUPOLEV
1888–1972
Developed over 100 different aircraft types, despite being imprisoned and closely guarded during Stalin's era.

30-SECOND TEXT
George Catalano

Engineers predict motion of flying objects using aerodynamics.

CONTROLLING POLLUTION

30-second foundation

Engineers have traditionally controlled pollution in two ways: either retaining and storing pollutants until a solution is found; or treating them to an acceptable level before discharging them. Both methods can be expensive, and strong government enforcement is needed for compliance. In developing nations with weak governance, pollutants can often be discharged without significant penalties. Engineers are developing exciting and profitable alternatives, such as cleaner production and industrial ecology. Cleaner production processes designed using 'green chemistry' bypass pollution problems entirely. For example, alumina-refining oxalate residues can be converted into sodium carbonate using bacteria. The sodium carbonate can then be converted into sodium hydroxide to be used in the alumina refining process. Waste containing pollutants from one enterprise can often be converted into valuable products for another. Breweries and food-processing factories generate waste that, instead of being discharged into water, can be converted by bacteria into nutrient-rich fertilizers, generating energy as well as additional income. Engineers adapt natural waste-processing systems for industrial use: man-made swamps with vegetation can be effective waste-processing factories.

3-SECOND CORE
Future industries will see pollutants as resources that are too valuable to discharge into the natural environment. Engineers can often adapt natural processes to convert pollutants into valuable products.

3-MINUTE IDEA
Government regulations, taxes and incentives to combat pollution enable engineers to develop solutions that provide greater value with stronger community acceptance. As engineers develop cheaper, more efficient techniques to maximize benefits, environmental solutions become profitable, and companies adopt them without needing regulations or incentives.

RELATED TOPICS
See also
ENVIRONMENTAL ENGINEERING
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RESOURCE SCARCITY
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3-SECOND BIOGRAPHIES

ROBERT UNDERWOOD AYRES
1932–
Formalized industrial ecology concepts.

GATZE LETTINGA
1936–
Developed high-rate anaerobic processes, which inspired contemporary industrial ecologists.

DONALD HUISINGH
1937–
Promotes the ecological modernization movement, arguing that productive use of natural processes can lead to sustainable prosperity.

30-SECOND TEXT
Raj Kurup

Today's pollution is tomorrow's resource, with waste transformed into raw material.