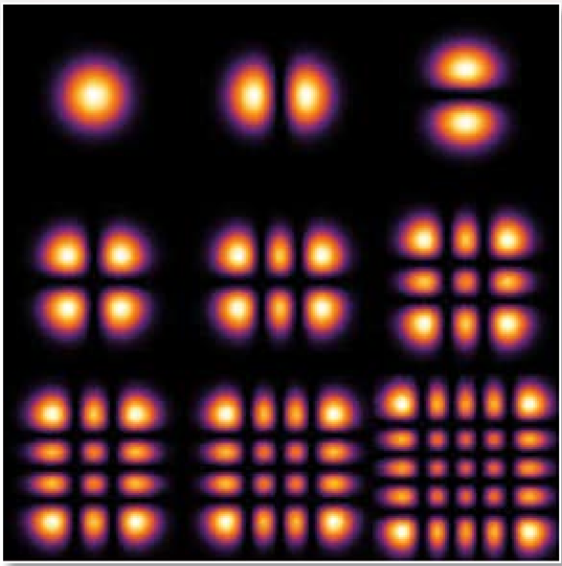
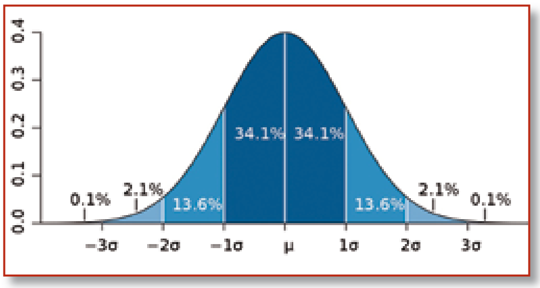
Shaping light

Modern micro-optical elements and adaptive mirrors exploit diffraction to shape light inside a laser. By **Andrew Forbes**, **Craig Long**, **Philip Loveday** and **Igor Litvin**.



When the laser operates in rectangular symmetry, the output light patterns (called modes) form 2D patterns of light following what are called Hermite–Gaussian functions. The number of null lines between the 'spots' of light correspond to the order of the functions – more spots, higher order.

The bell curve – or normal distribution



Dark blue is less than one standard deviation from the mean. For the normal distribution, this accounts for about 68% of the set (dark blue), while two standard deviations from the mean (medium and dark blue) account for about 95%, and three standard deviations (light, medium, and dark blue) account for about 99.7%.

The normal distribution, or bell curve, is a curve that describes any data that tend to cluster about a mean (average) figure, for example, the heights of men or women in a specific population. The standard deviation is a measure of variation from this mean. The curve describes the probability of a particular data point occuring in a specific population.

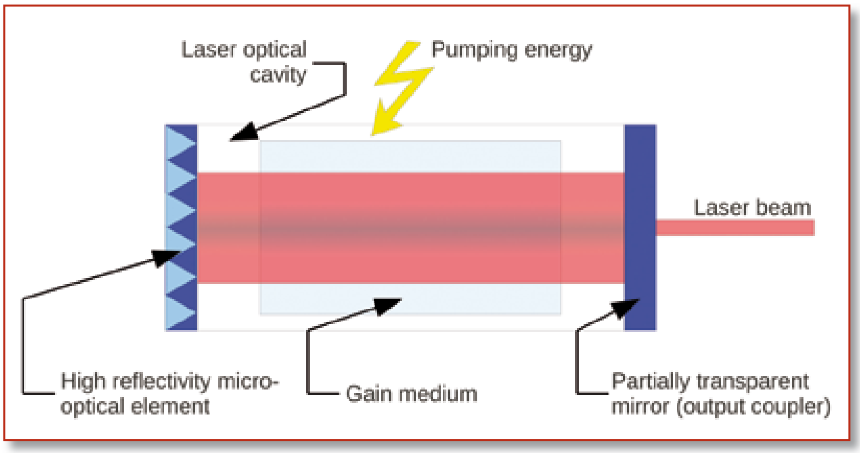
In lasers, the intensity of light across a beam will form a bell curve.

Back to basics

LASER (Light Amplification by the Stimulated Emission of Radiation) light can easily be distinguished from other light sources (such as torches) by its brightness and directionality. This can be demonstrated at home by holding a laser pointer in one hand and a torch in the other, and shining both towards a wall at the opposite end of a room: the laser light will be concentrated in a small bright spot, whereas the torch light will be far more diffuse. This property is as a result of what is known as coherence, a measure of how 'in-step' the emitted photons of light are. Coherent light can be made to interfere with itself, in a way that is similar to the way in which ripples on a pond interact. As a result, it is possible to take some light, add some more light to it, and the result will be no light! This never happens with torch light (unless you pass it through a very small pin-hole) but it does happen with laser light, since laser light is coherent while torch light is not.

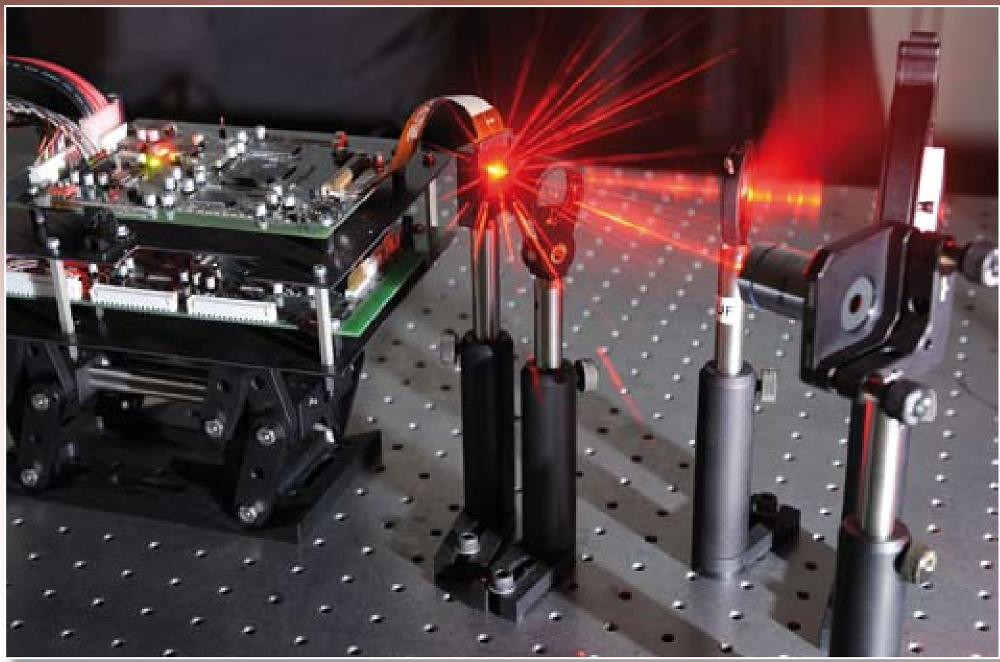
So, how is laser light produced? When a material is supplied with energy the atoms in the material become excited, resulting in electrons jumping to higher, unstable, energy levels. When an excited electron returns to its original energy level a light particle, or photon, is emitted. You encounter this phenomenon every day; this is the process that causes a heater element in a toaster, or a torch light bulb filament, to glow when supplied with electrical energy. This does not, however, mean that your toaster is a laser! In a toaster or a light bulb, photons are released randomly, while in a laser the photons are released coherently through a process known as stimulated emission. An atom with excited electrons encountering a photon with certain properties, such as direction and frequency, tends to release photons with similar properties. These two similar photons will then interact with other high-energy atoms releasing even more 'in-step' photons, and so on.

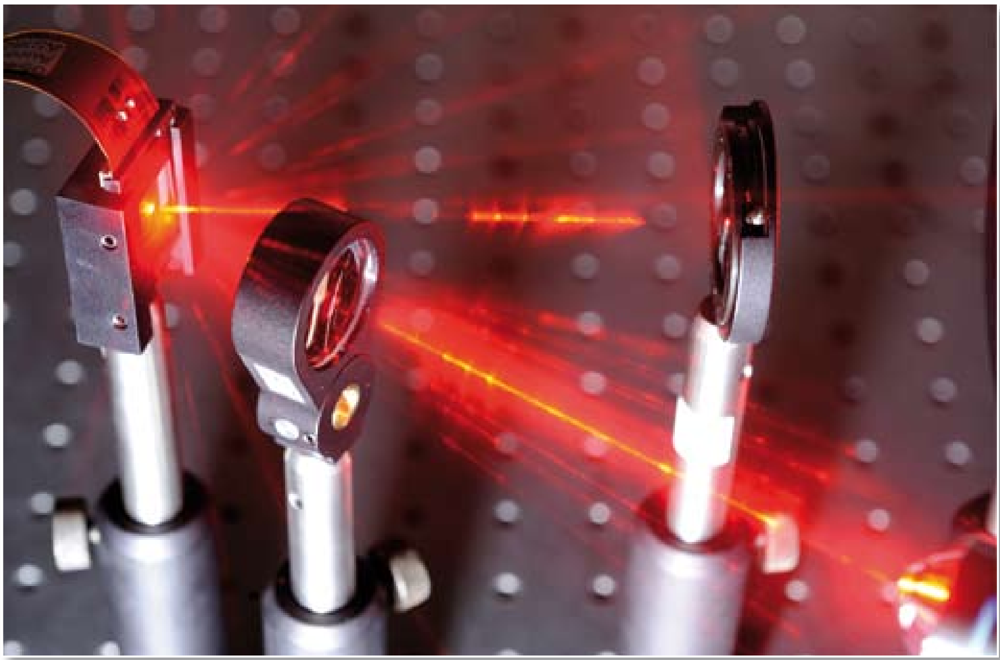
To make a laser one therefore requires only three basic ingredients. First, we need a transparent or semi-transparent substance capable of amplifying light. That is to say, if we put some light in, we would like to get even more light out. We call this the gain medium. Unfortunately no medium exists that will amplify light without some form of excitation, so our second requirement is an excitation system. In many lasers this is simply an electrical current, but in some more exotic lasers in the former Soviet Union the excitation was a nuclear bomb, so it really only depends on what you want to do, and how crazy the scientists are!



A schematic of a laser, showing the three core components: the resonator bound by the two end mirrors, a gain medium, and a means to excite the gain medium.

Left: The rainbow colours on the readable surface of a compact disc (CD). Image: Wikimedia commons





Top and above: Light can be shaped outside a laser by using spatial light modulators – liquid crystal devices for creating digital holograms to mimic DOEs. Light diffracts off these devices into a wide range of diffraction orders, as shown by these long exposure pictures. Image: CSIR

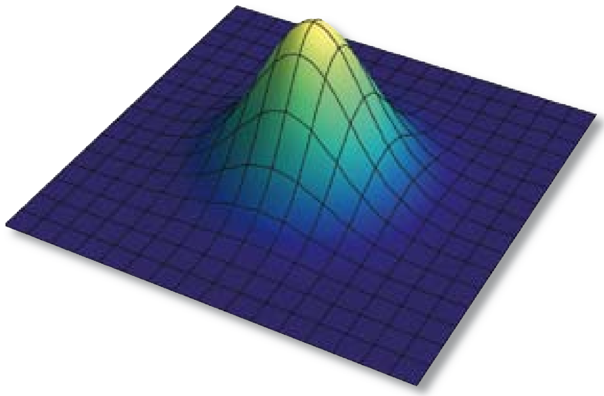
The excited gain medium has what is called a population inversion (it contains more atoms in an excited state than at a lower energy state). Laser light requires stimulated emission, and Einstein showed that this benefits from a strong field of photons. Thus, the third requirement is a box that keeps the light bouncing back and forth inside the gain medium, so that more stimulated emission takes place. This 'box', or resonator, is usually made of two mirrors, one of which is partially transmitting so that on each pass a little of the light is let out of the box. While the gain medium determines the wavelength (and therefore the colour) of the laser light, the resonator determines the shape of the light. Laser beams usually have a Gaussian intensity distribution with a smooth profile following the well-known Bell curve function – they have a high peak intensity at the centre which slowly drops to zero at the edges of the beam. If the optical elements inside the resonator are custom designed however, it is possible to create laser beams with very complicated cross-sectional patterns.

We refer to this as shaping the light inside the laser, and typically we do this with diffractive optical elements (DOEs).

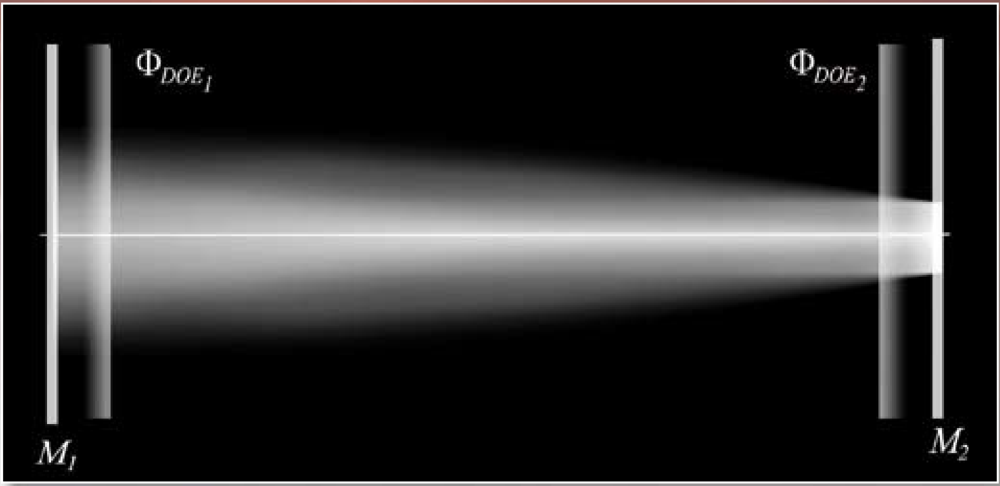
Shaping light with DOEs

When encountering an obstacle, travelling waves such as light, may be reflected, refracted and/or diffracted. For pure reflection or refraction, obstacles such as mirrors or lenses are much larger (mm to cm range) than the wavelength of light (400-700 nm for visible light). Although diffraction may not be as well known, it is just as common as reflection and refraction. Diffraction is what gives the bottom of a CD that rainbow effect, caused by light interacting with the spiral pattern of tiny, closely spaced, alternating flat and raised lines on the bottom of a CD.

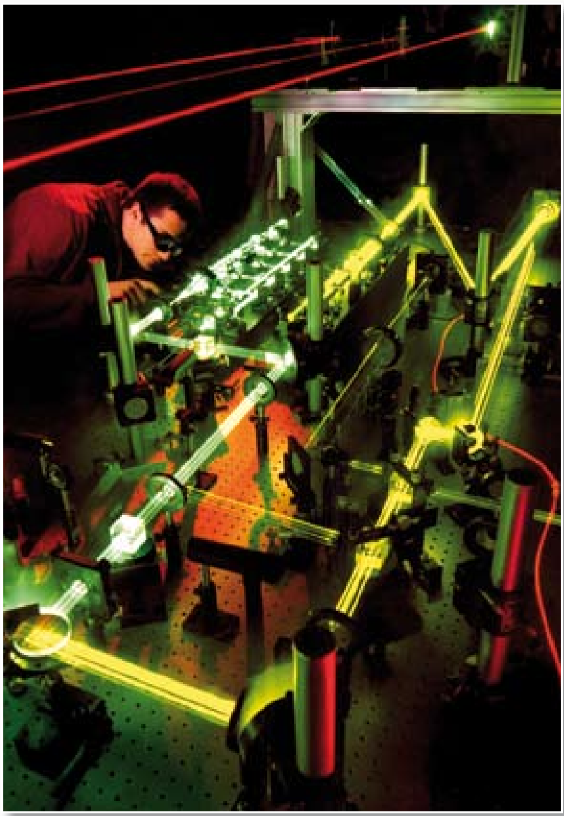
Diffraction is most pronounced when features are comparable in size to the wavelength of the light passing through (or reflected off) them, and the resulting field is an interference pattern. The distinguishing property of DOEs is therefore the feature sizes on the optical element. If the DOE is designed carefully, this interference pattern can take on almost any shape – customised light! This shaping of laser beams can be done external to the laser, but there are advantages in doing it inside the resonator: no additional optics and fewer optical alignment problems. We routinely create such patterns digitally in our laboratory for the creation of vortex beams and non-diffracting beams for the optical trapping and tweezing of miniature particles and biological specimens.▷▷



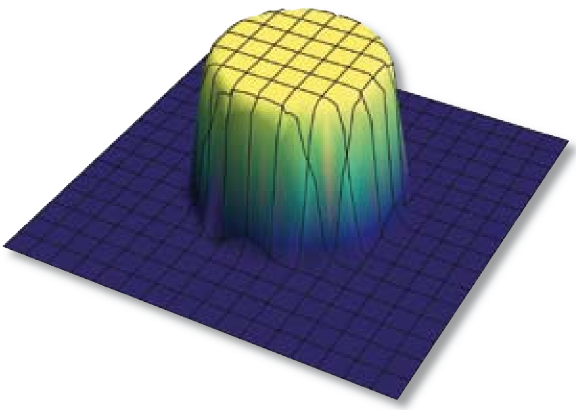
A Gaussian profile laser beam, with a characteristic peak at the centre and slow decay at the edges.



The resonator concept, as shown here, comprises two transparent DOEs (like lenses) at either end as well as the usual bounding mirrors to complete the box.



A technician evaluates the interaction of multiple lasers that will be used aboard the Airborne Laser. Image: Wikimedia commmons



A fat-top profile laser beam; such beams have a constant energy density in the central part of the beam, that sharply falls to zero at the edges.

Keeping light in shape with adaptive optics

In practice, it is not possible to create a perfect optical component or system, and there are always small errors due to manufacture, assembly, and so on. Furthermore, as the laser works it heats up and components may expand slightly or experience other temperature- or time-dependent changes. It is possible to measure this error continuously at the point where the beam exits the resonator using a special piece of equipment called a wavefront sensor. Using this information, we can calculate how the laser beam should be modified in such a way that the best beam quality is maintained, and all we then need is to appropriately adjust an optical element to correct the wavefront. This is known as adaptive optics. Similar techniques are used to eliminate the effects of atmospheric turbulence in large telescopes, such as the Southern African Large Telescope (SALT) in Sutherland. Using small actuators located behind a mirror it is indeed possible to manipulate the beam slightly to compensate for these errors, and thereby ensure that the laser is functioning optimally. This way, if we wanted a Gaussian beam from the laser for example, we get a Gaussian beam.

Laser beams made to order

Gaussian laser beams are popular because they propagate with a very small rate of spreading, and so are ideal for long-distance communication and military applications. Unfortunately they fill a very small region of the gain medium inside the laser, so there's a lot of the gain material not being used. As a result, there is always a choice between having a good laser beam (Gaussian) or a laser with lots of energy but which is not Gaussian. For example, in recent experiments the Gaussian beam could be produced from a laser using standard techniques, but then the energy was 25 times less than the maximum without a Gaussian shape!

In a ground-breaking development, we have designed DOEs to create a very special laser beam – one that changes (metamorphosis) from one shape to another when travelling inside the laser resonator, so that we can have different shapes at the two resonator mirrors: a smooth 'Gaussian' beam at one end, and a 'flat' beam at the other.

This metamorphosis obeys the wave equation, which predicts how these fields propagate, but the custom phase of the light ensures a more complex propagation across the resonator than would usually be observed. By designing our resonator to have the flat beam at the one end, we can extract high energy, while the metamorphosis ensures that all this energy goes into the ideal Gaussian laser beam – the best of both worlds!

By selecting the Gaussian beam by a DOE we are ensuring that no energy is lost in the process. It was previously thought that such beams cannot be selected by phase because they share the same phase function as many other types of beams, so distinguishing them would be difficult. We have now shown that the metamorphosis idea circumvents this problem, thus demonstrating a key technology that will revolutionise laser design in the future. At the moment high-energy lasers with good laser beams require very large and expensive systems. For example, the USA Air Force Airborne Laser, a high-power laser to shoot down missiles, fills an entire Boeing 747!

By customising the laser resonator it is possible to design light to order. Laser technology has been around for 50 years, yet new research and ideas are ensuring that it will remain an active area of investigation for years to come. □

Professor Andrew Forbes is Chief Researcher and Research Group Leader at the CSIR National Laser Centre, and holds honorary positions in the Schools of Physics at both the University of Stellenbosch and the University of KwaZulu-Natal.

Dr Craig Long is a Senior Researcher at CSIR Material Science and Manufacturing.

Dr Philip Loveday is a Principal Researcher and Research Group Leader at the CSIR Material Science and Manufacturing division.

Dr Igor Litvin has recently graduated with his PhD and has joined the CSIR National Laser Centre as a Senior Researcher.

The atom

The atom is a basic unit of matter. It is made up of a dense (heavy) central nucleus, surrounded by a cloud of negatively charged particles that are called electrons.

An electron is a sub-atomic (smaller than an atom) particle that carries a negative electrical charge.

A proton is a sub-atomic particle that carries an electrical charge of +1. Protons can also exist on their own – the hydrogen ion (H+) is a proton. The number of protons in a nucleus is the atomic number and this defines the type of element (pure chemical substance) that the atom forms.

A neutron is a sub-atomic particle with no electrical charge. Its mass is slightly larger than that of a proton.

The nucleus of an atom is a mixture of positively charged protons and electrically neutral neutrons. The electrons of an atom are bound to the nucleus by the electromagnetic force that is generated by the electrical charges they carry. More than 99.9% of an atom's mass is concentrated in the nucleus.

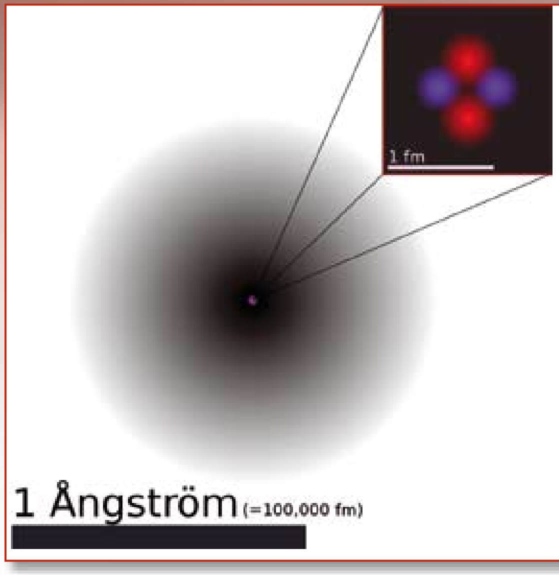
Electrons that are bound to atoms have a stable set of energy levels, which are also called orbitals, and these electrons can move between these energy levels by absorbing or emitting photons (light particles) that match the energy difference between these levels. Electrons determine the chemical properties of an element and also its magnetic properties.

Bohr referes to the atomic physicist, Neils Bohr, who was one of the first people to describe the energy levels of the electrons in an atom.

Atoms and elements

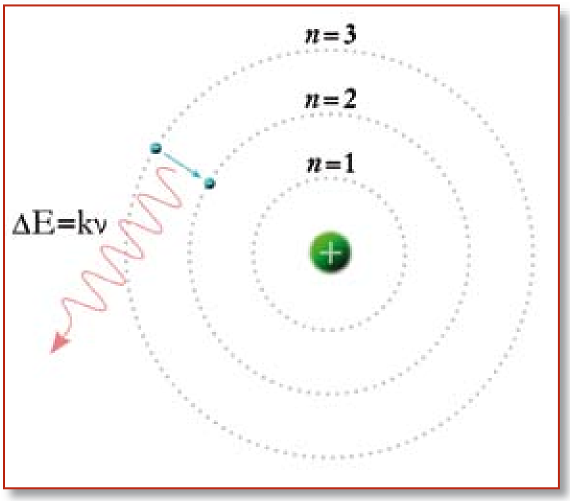
A chemical element is a pure chemical substance that is made up of one type of atom. Each element has a specific atomic number, which is the number of protons in its nucleus. Common examples of elements are iron, copper, silver, gold and oxygen. At the time of writing 118 elements have been observed, 92 of which occur naturally on the Earth. The rest are synthetic elements that have been produced artificially in particle accelerators. Oxygen is the most abundant element in the Earth's crust.

The number at the top of each element is its atomic number.



Top right: A depiction of the atomic structure of the helium atom. The magnified nucleus is schematic, showing protons in pink and neutrons in purple.

Image: Wikimedia commons



Right: A simple diagram to show the orbitals of an atom according to the Bohr model. The red line depicts an electron jumping between these levels.

Image: Wikimedia commmons

Below: The periodic table of the elements.

Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
Lanthanides				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr