Engineering Physics:

Physics of Materials: Crystal Structure

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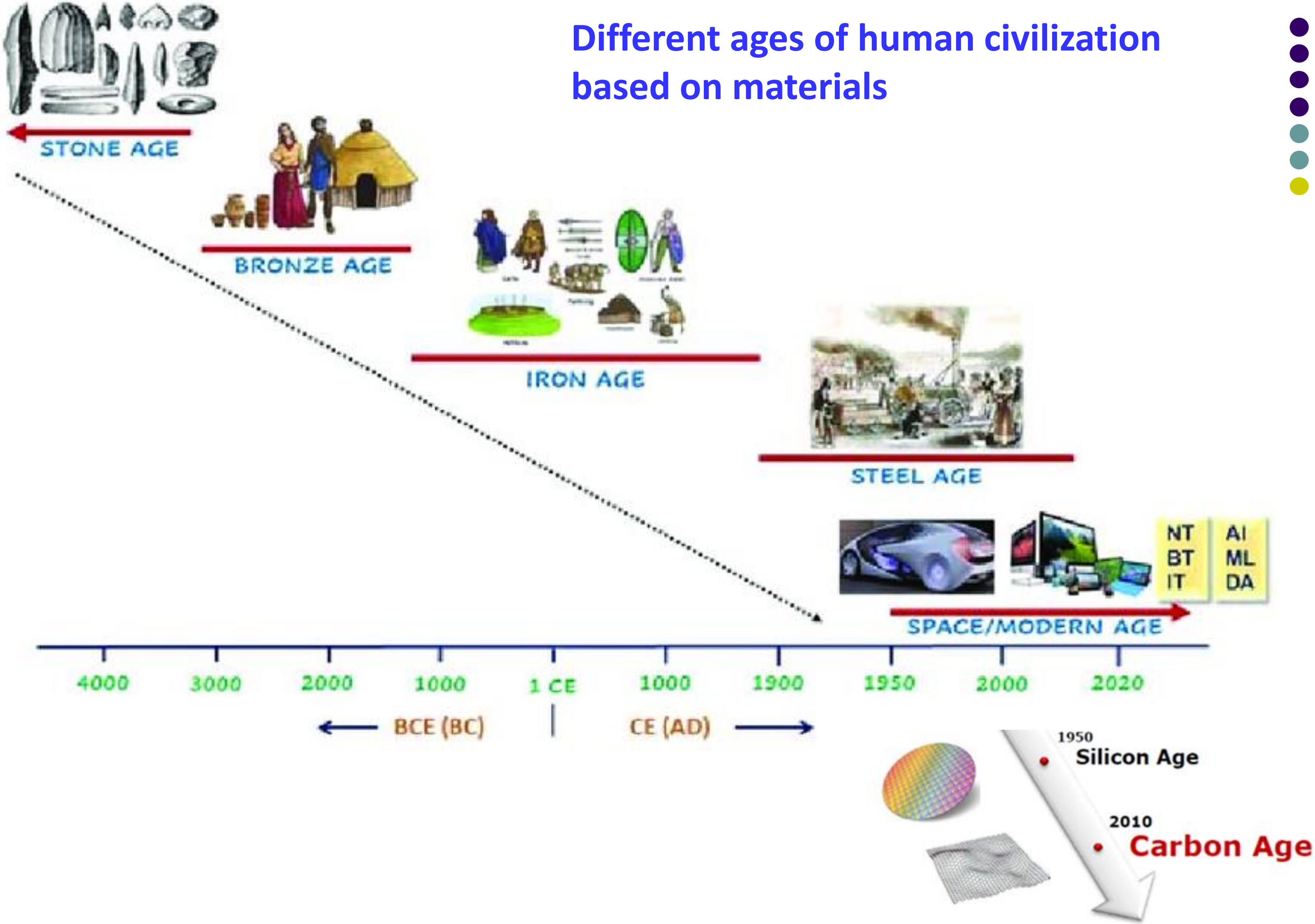
Different ages of human civilization based on materials




Greatest Engineering Achievements
OF THE 20TH CENTURY
About
Timeline
The Book
Welcome!
How many of the 20th century's greatest engineering achievements will you use today? A car? Computer? Telephone? Explore our list of the top 20 achievements and learn how engineering shaped a century and changed the world.
1. Electrification
2. Automobile
3. Airplane
4. Water Supply and Distribution
5. Electronics
6. Radio and Television
7. Agricultural Mechanization
8. Computers
9. Telephone
10. Air Conditioning and Refrigeration
11. Highways
12. Spacecraft
13. Internet
14. Imaging
15. Household Appliances
16. Health Technologies
17. Petroleum and Petrochemical Technologies
18. Laser and Fiber Optics
19. Nuclear Technologies
20. High-performance Materials
Greatest Achievements
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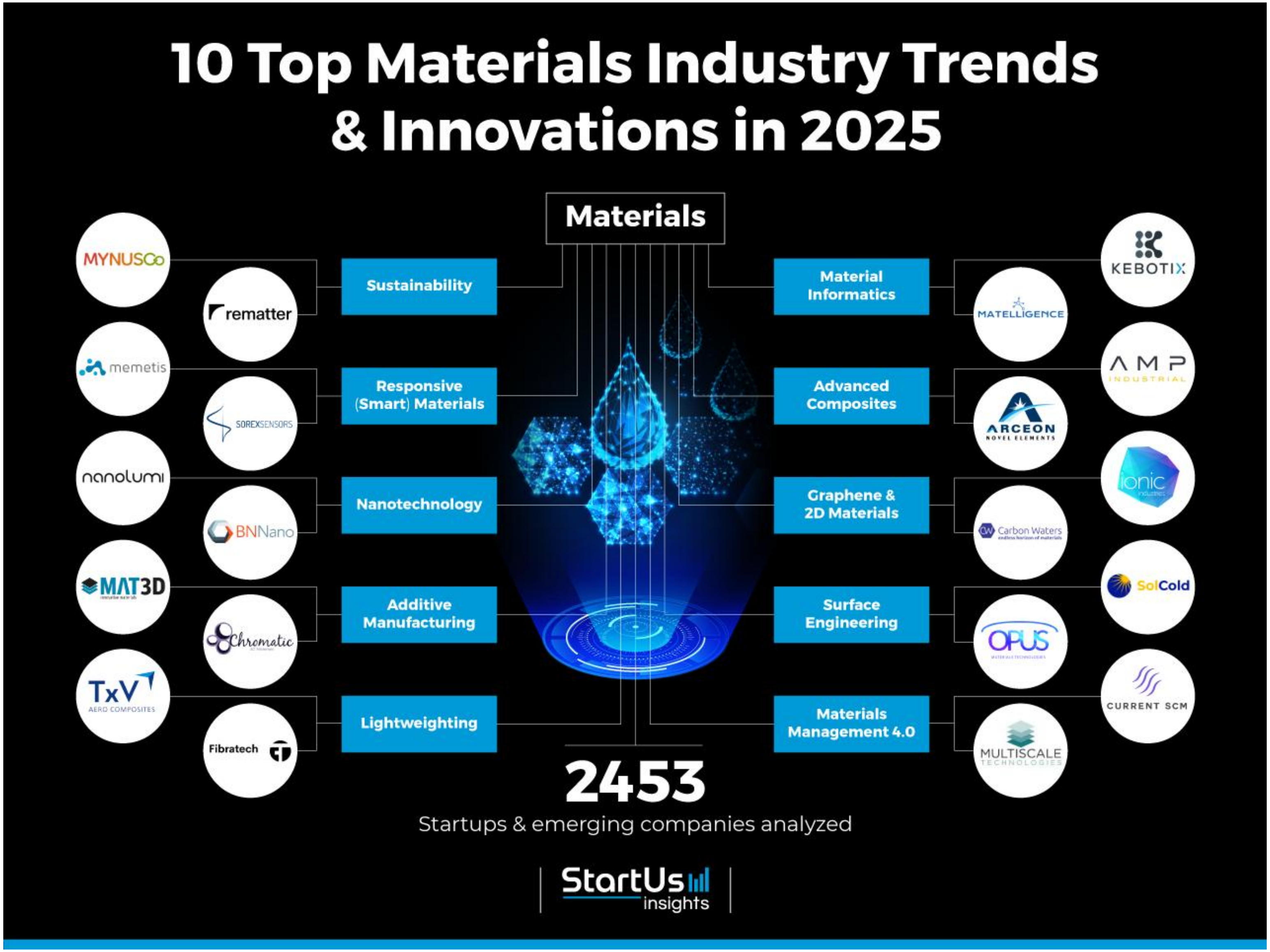
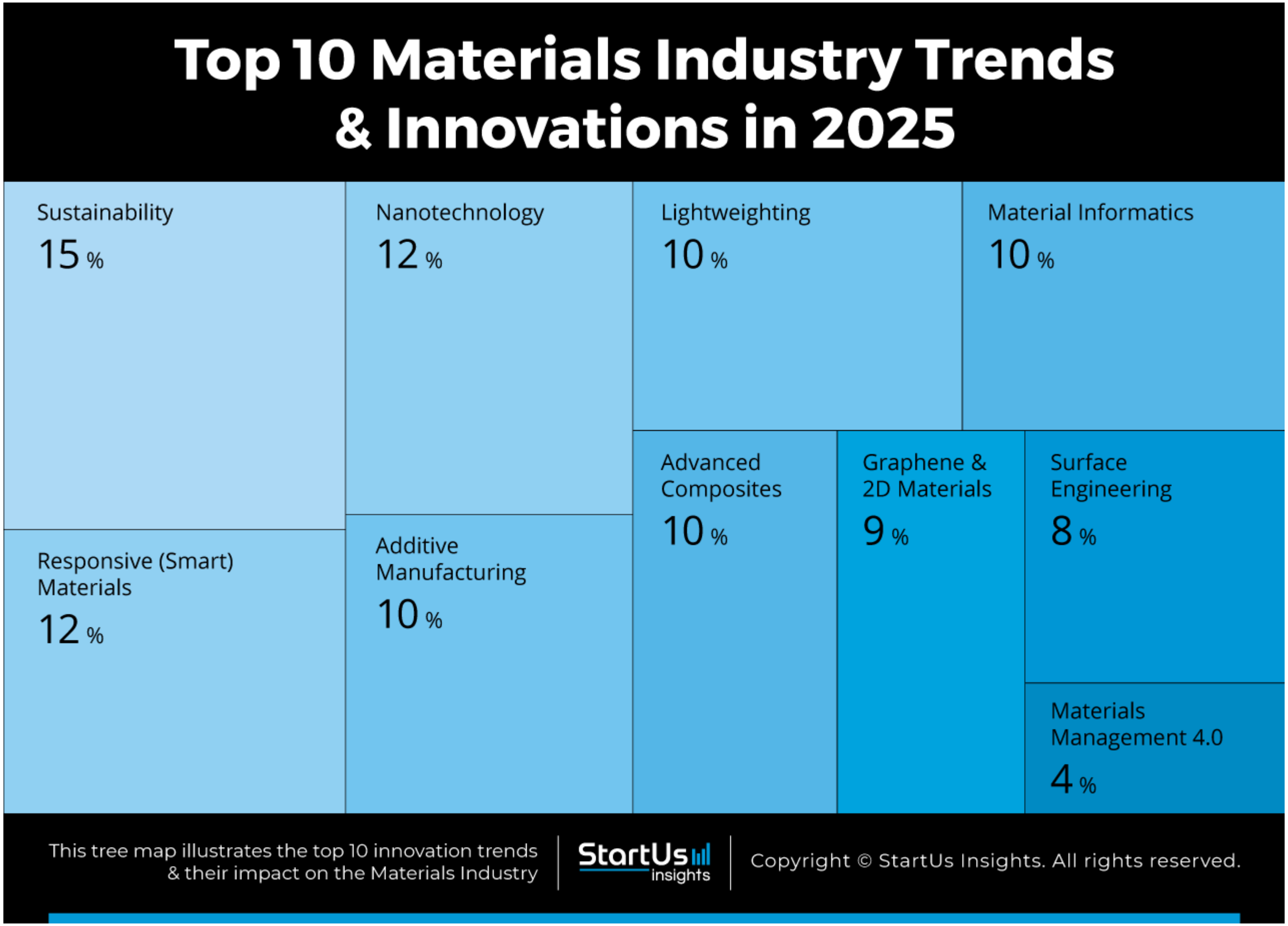


10 Top Materials Industry Trends & Innovations in 2025
Materials
Sustainability
Responsive (Smart) Materials
Nanotechnology
Additive Manufacturing
Lightweighting
Material Informatics
Advanced Composites
Graphene & 2D Materials
Surface Engineering
Materials Management 4.0
MYNUSCo
rematter
memetis
SOREXSENSORS
nanolumi
BNNano
MAT3D
Chromatic
TxV
AERO COMPOSITES
Fibratech
KEBOTIX
MATELLIGENCE
AMP
INDUSTRIAL
ARCEON
NOVEL ELEMENTS
ionic
Carbon Waters
SolCold
OPUS
CURRENT SCM
MULTISCALE
TECHNOLOGIES
2453
Startups & emerging companies analyzed
StartUs insights


Top 10 Materials Industry Trends
& Innovations in 2025
Sustainability 15 %
Nanotechnology 12 %
Lightweighting 10 %
Material Informatics 10 %
Responsive (Smart) Materials 12 %
Additive Manufacturing 10 %
Advanced Composites 10 %
Graphene & 2D Materials 9 %
Surface Engineering 8 %
Materials Management 4.0 4 %
This tree map illustrates the top 10 innovation trends & their impact on the Materials Industry
StartUs insights
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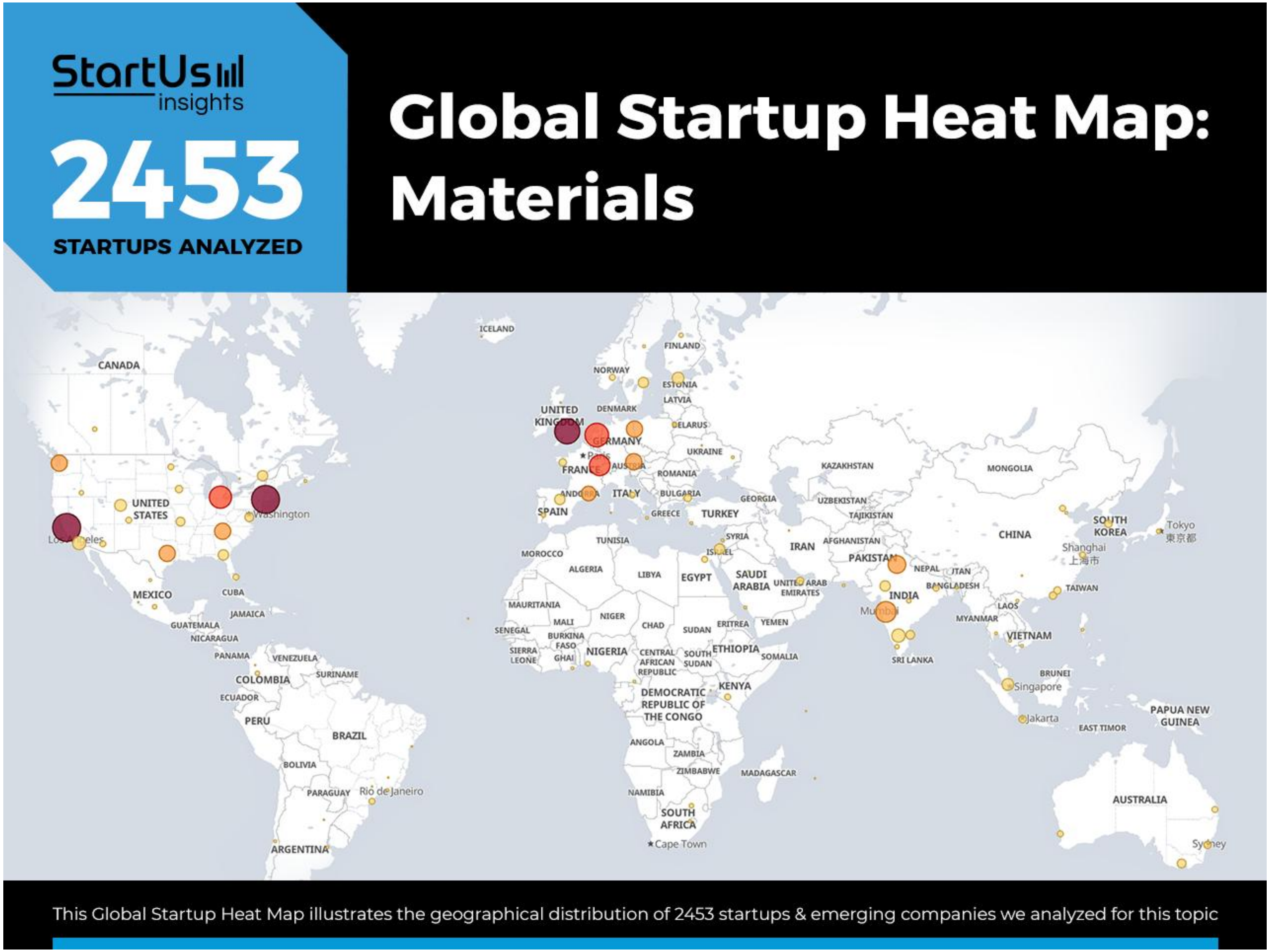
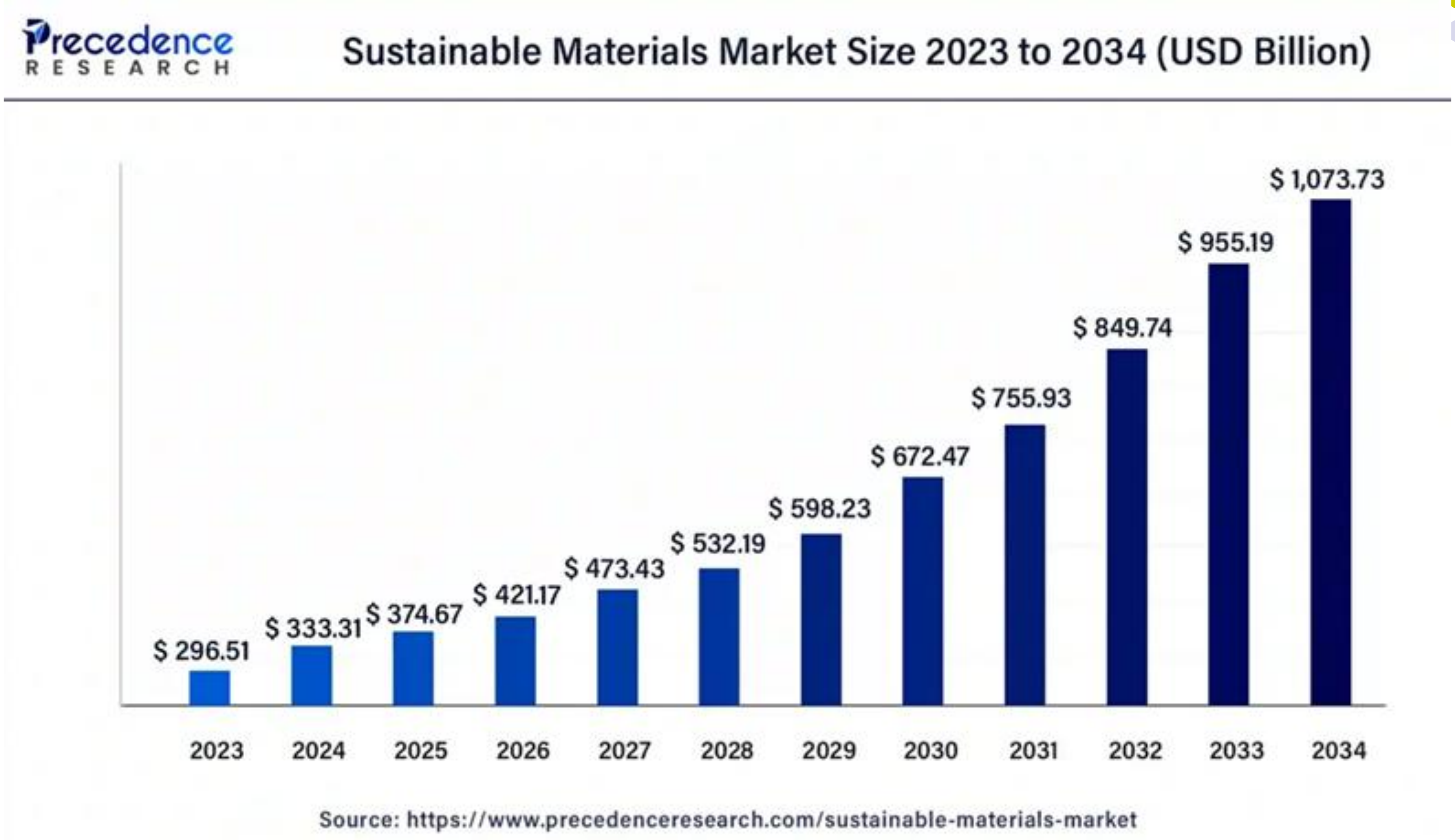
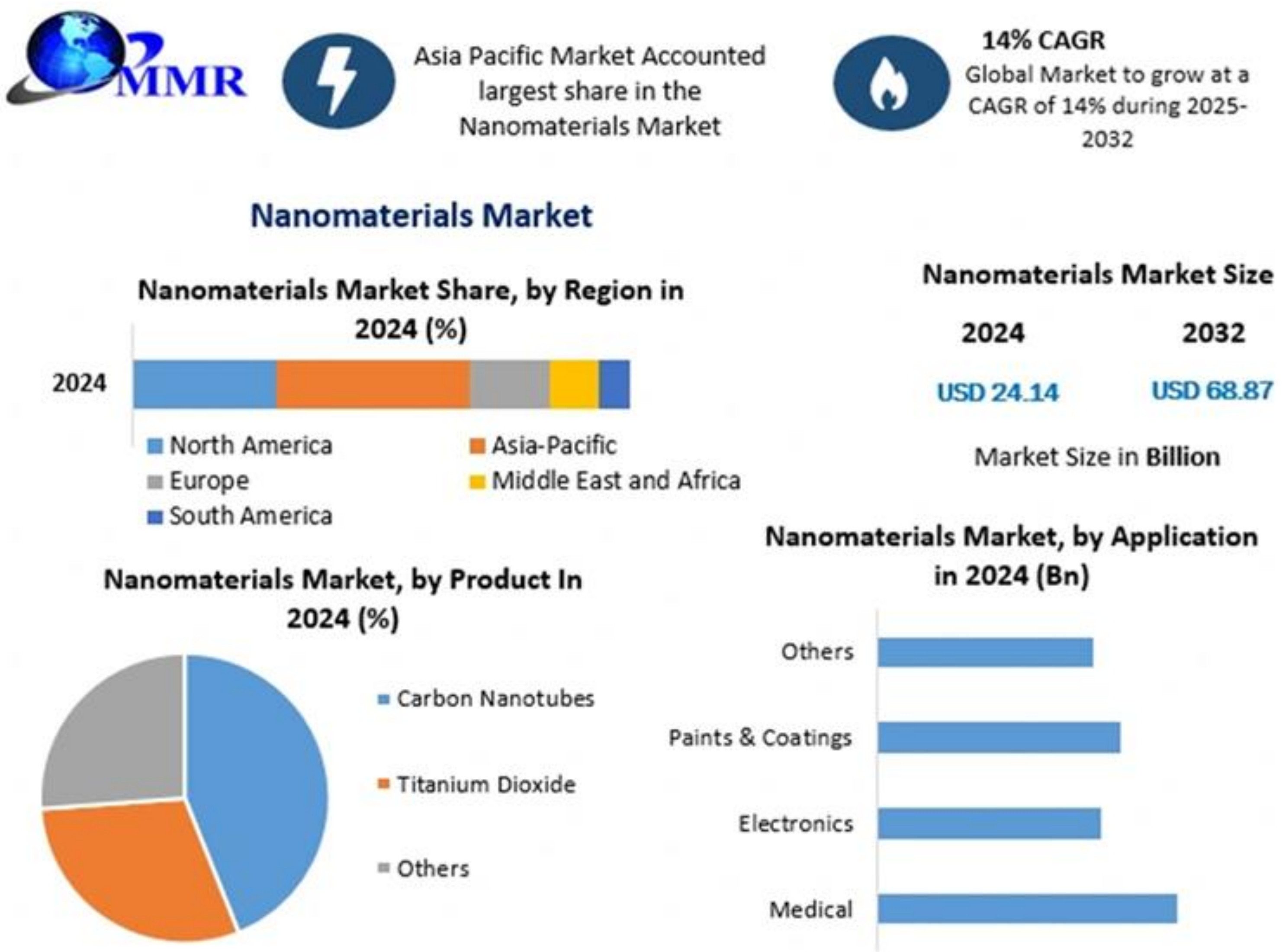
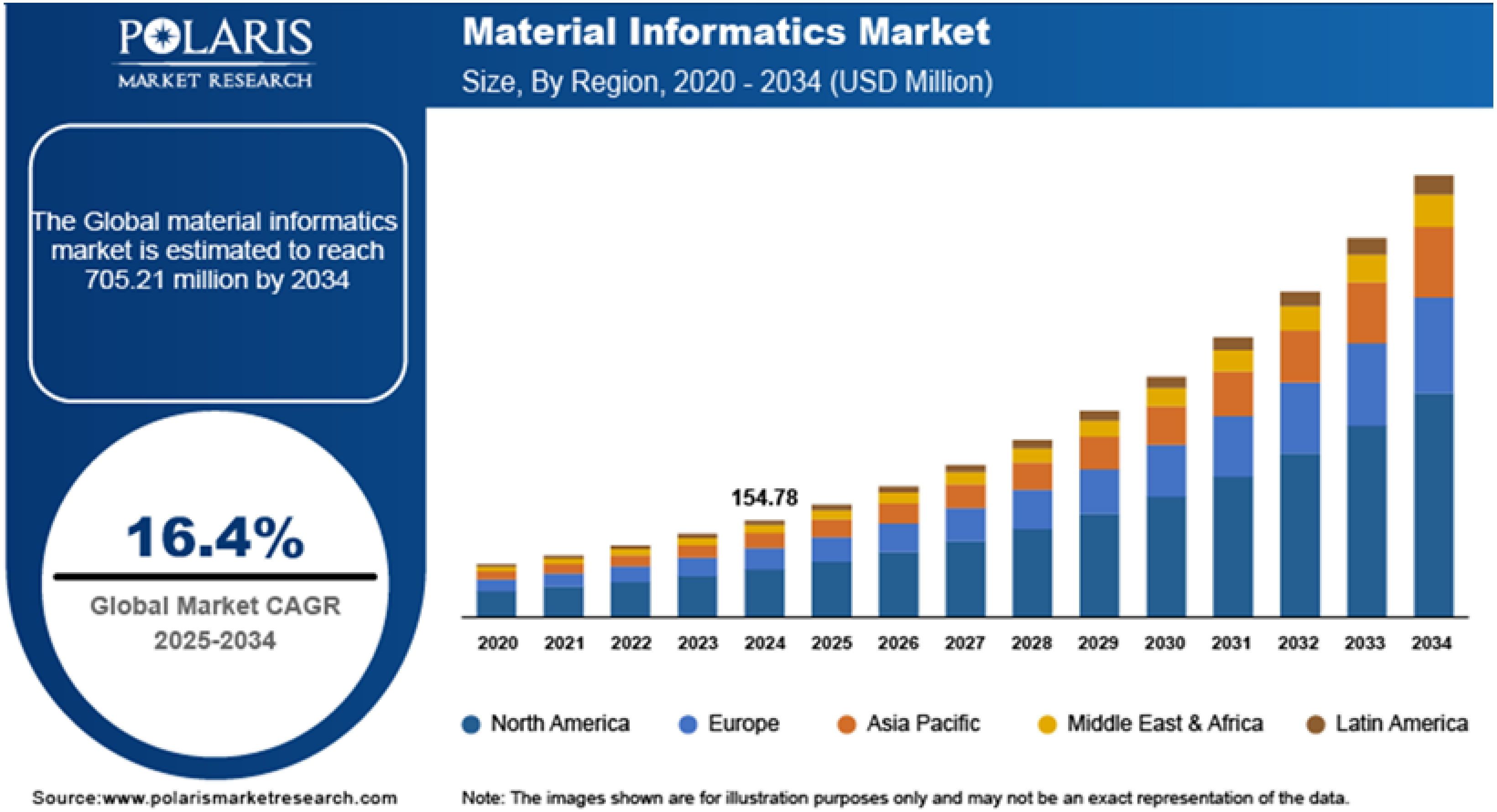

StartUs insights
2453
STARTUPS ANALYZED
Global Startup Heat Map: Materials
CANADA
UNITED STATES
MEXICO
CUBA
JAMAICA
GUATEMALA
NICARAGUA
PANAMA
VENEZUELA
SURINAME
COLOMBIA
ECUADOR
PERU
BRAZIL
BOLIVIA
PARAGUAY
Rio de Janeiro
ARGENTINA
Washington
ICELAND
FINLAND
NORWAY
ESTONIA
LATVIA
UNITED KINGDOM
DENMARK
BELARUS
GERMANY
UKRAINE
FRANCE
AUSTRIA
ROMANIA
ANDORRA
ITALY
BULGARIA
SPAIN
GREECE
TURKEY
GEORGIA
MOROCCO
TUNISIA
ALGERIA
LIBYA
EGYPT
SYRIA
ISRAEL
SAUDI ARABIA
UNITED ARAB EMIRATES
IRAN
MAURITANIA
MALI
NIGER
CHAD
SUDAN
ERITREA
YEMEN
SENEGAL
BURKINA FASO
SIERRA LEONE
GHANA
NIGERIA
CENTRAL AFRICAN REPUBLIC
SOUTH SUDAN
ETHIOPIA
SOMALIA
KENYA
DEMOCRATIC REPUBLIC OF THE CONGO
ANGOLA
ZAMBIA
ZIMBABWE
MADAGASCAR
NAMIBIA
SOUTH AFRICA
Cape Town
KAZAKHSTAN
UZBEKISTAN
TAJIKISTAN
AFGHANISTAN
PAKISTAN
NEPAL
BHUTAN
BANGLADESH
INDIA
Mumbai
SRI LANKA
MONGOLIA
CHINA
SOUTH KOREA
Tokyo
東京都
Shanghai
上海市
TAIWAN
LAOS
MYANMAR
VIETNAM
BRUNEI
Singapore
Jakarta
EAST TIMOR
PAPUA NEW GUINEA
AUSTRALIA
Sydney
This Global Startup Heat Map illustrates the geographical distribution of 2453 startups & emerging companies we analyzed for this topic

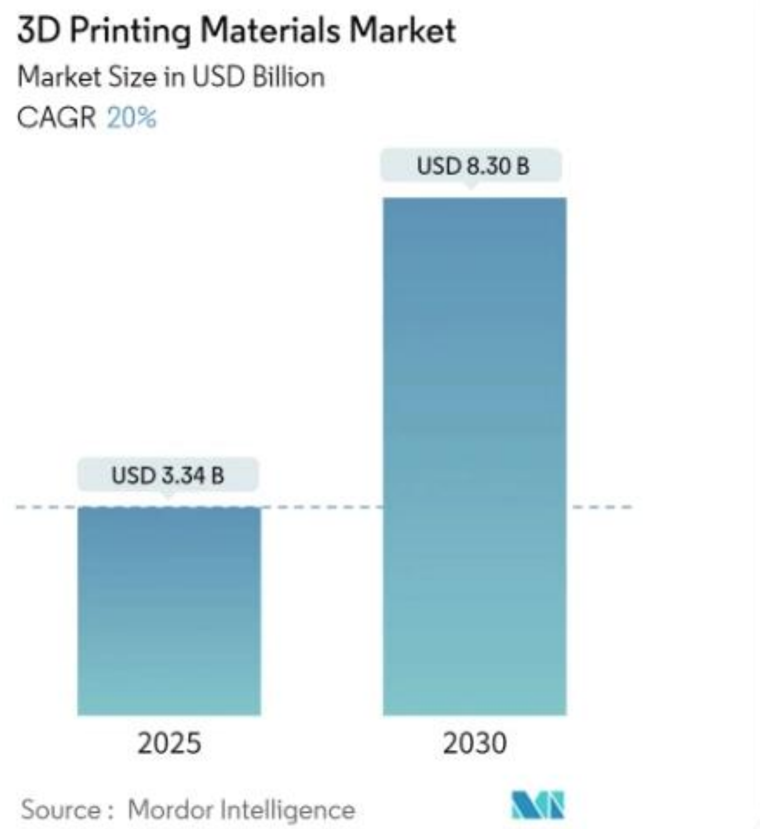

Precedence RESEARCH
Sustainable Materials Market Size 2023 to 2034 (USD Billion)
$ 296.51
$ 333.31
$ 374.67
$ 421.17
$ 473.43
$ 532.19
$ 598.23
$ 672.47
$ 755.93
$ 849.74
$ 955.19
$ 1,073.73
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
Source: https://www.precedenceresearch.com/sustainable-materials-market


MMR
Asia Pacific Market Accounted largest share in the Nanomaterials Market
14% CAGR
Global Market to grow at a CAGR of 14% during 2025-2032
Nanomaterials Market
Nanomaterials Market Share, by Region in 2024 (%)
2024
North America
Asia-Pacific
Europe
Middle East and Africa
South America
Nanomaterials Market Size
2024
2032
USD 24.14
USD 68.87
Market Size in Billion
Nanomaterials Market, by Product In 2024 (%)
Carbon Nanotubes
Titanium Dioxide
Others
Nanomaterials Market, by Application in 2024 (Bn)
Others
Paints & Coatings
Electronics
Medical



Large companies today are adopting a data-driven approach to materials, utilizing informatics, computational techniques, and machine learning (ML), and artificial intelligence (AI). This approach enables them to systematically organize and model materials data.

The material informatics market, valued at USD 154.78 million in 2024, is expected to grow from USD 179.92 million in 2025 to USD 705.21 million by 2034, with a CAGR of 16.4% during 2025–2034.



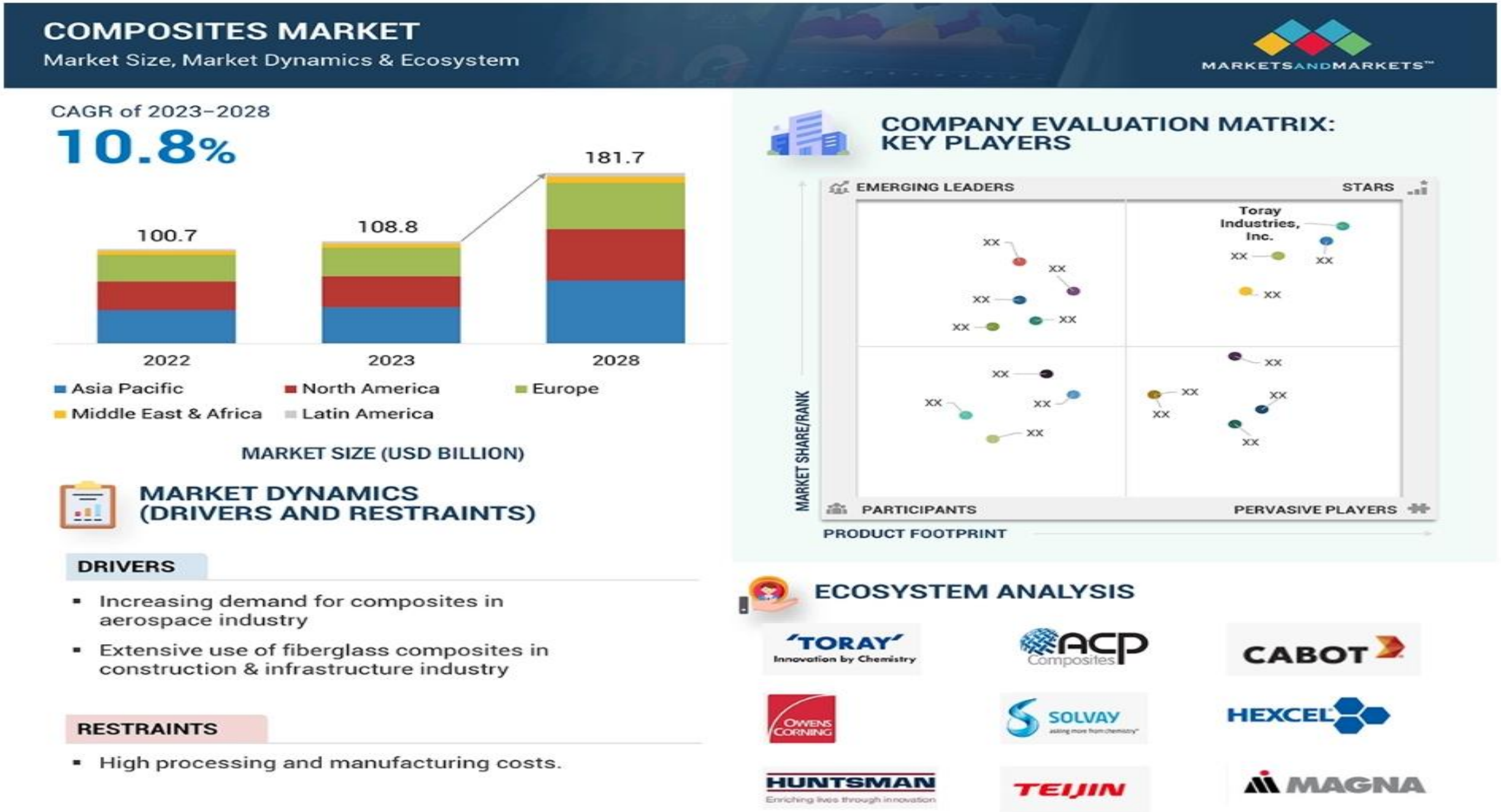
Study Period	2019 - 2030
Market Size (2025)	USD 3.34 Billion
Market Size (2030)	USD 8.30 Billion
CAGR (2025 - 2030)	20.00 %
Fastest Growing Market	Asia Pacific
Largest Market	North America
Market Concentration	High

Major Players

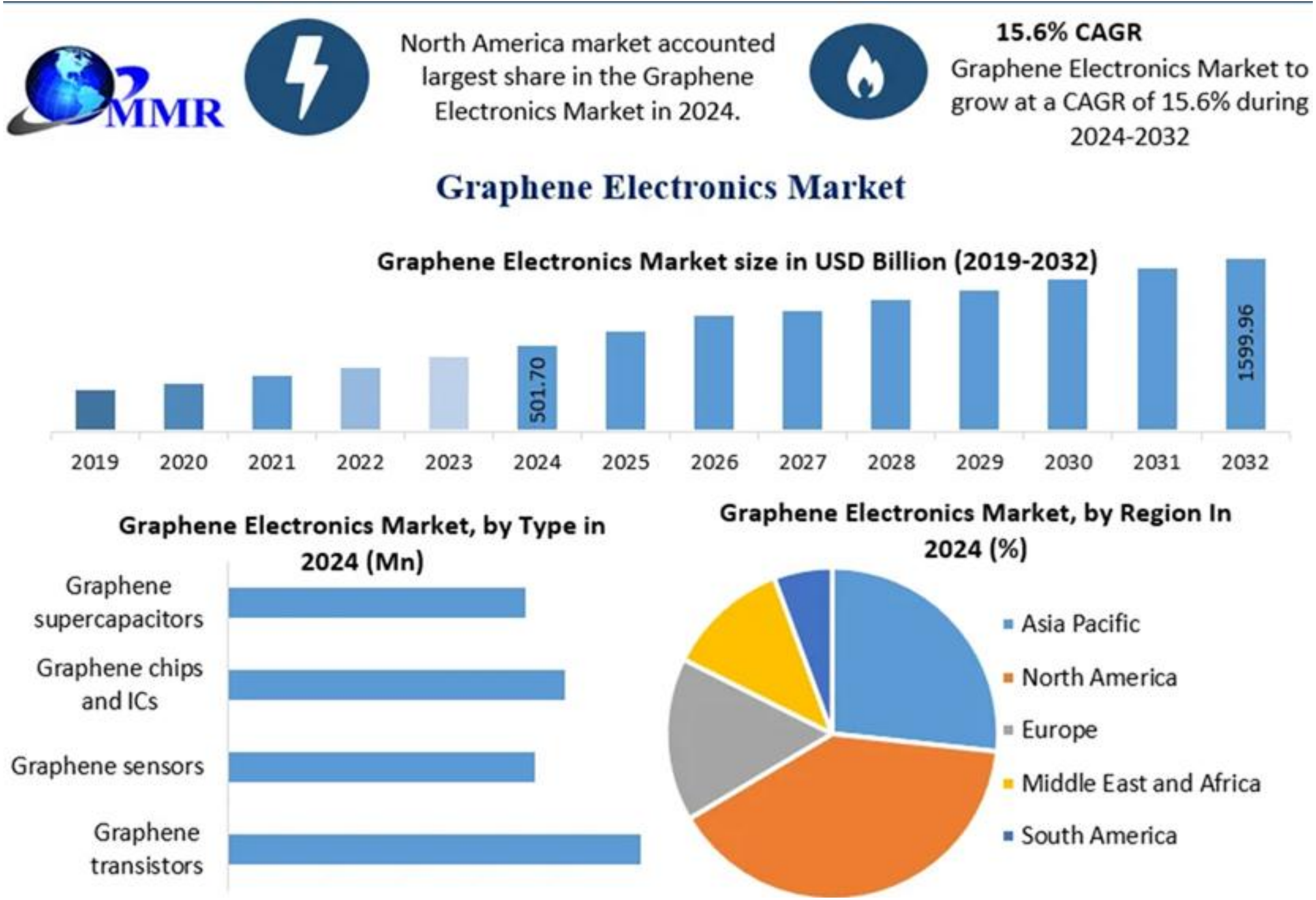
*Disclaimer: Major Players sorted in no particular order

Emerging additive manufacturing facilities are evolving beyond traditional thermoplastics, focusing on materials that offer greater flexibility, customization, functionality, and produce less waste. The advancement of 3D printing technologies is driving improvements in metals, alloys, ceramics, fibers, and their compounds.

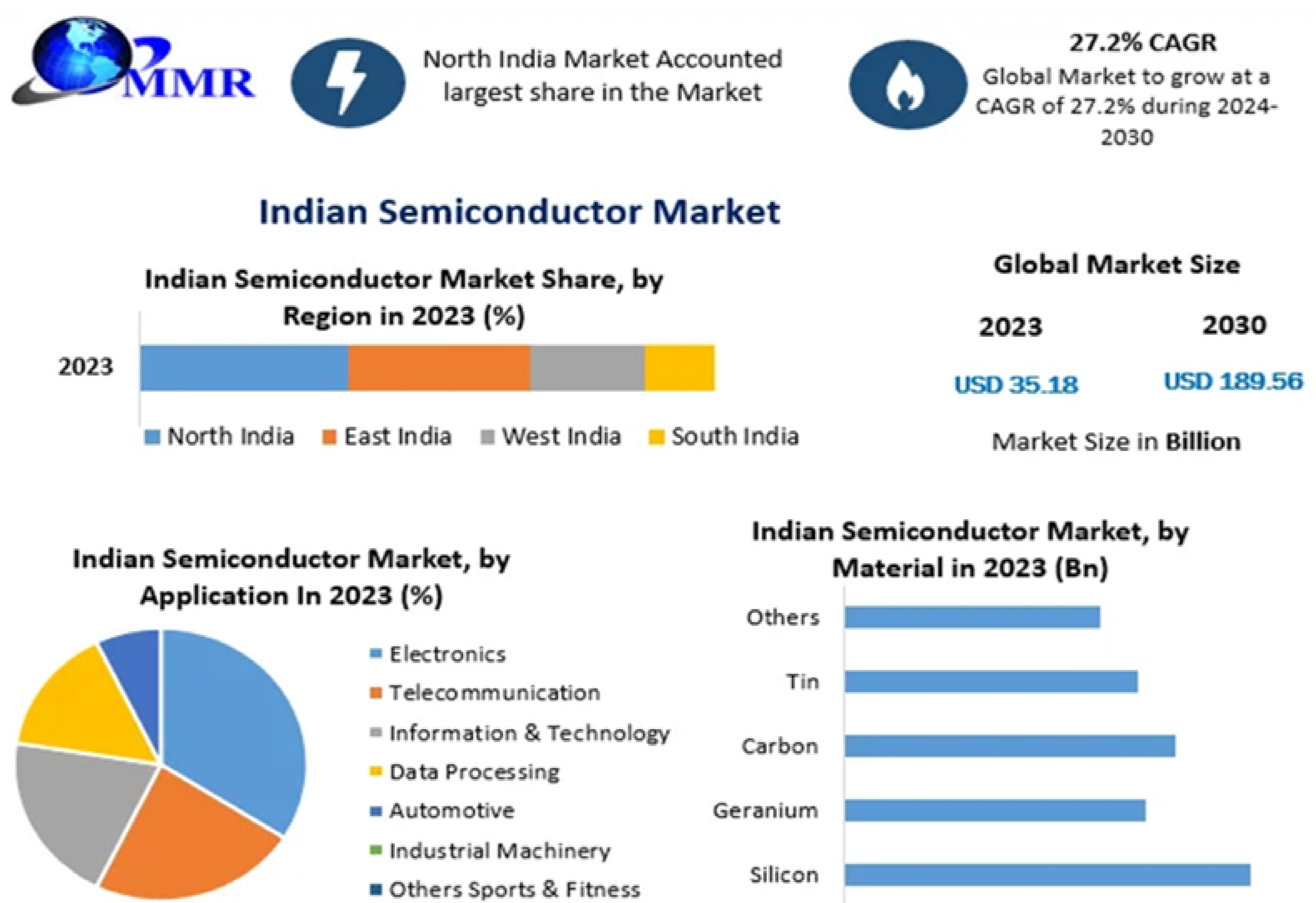
3D printing is also fostering the development of new, durable polymer filaments with enhanced conductance, melting, and chemical resistance properties.

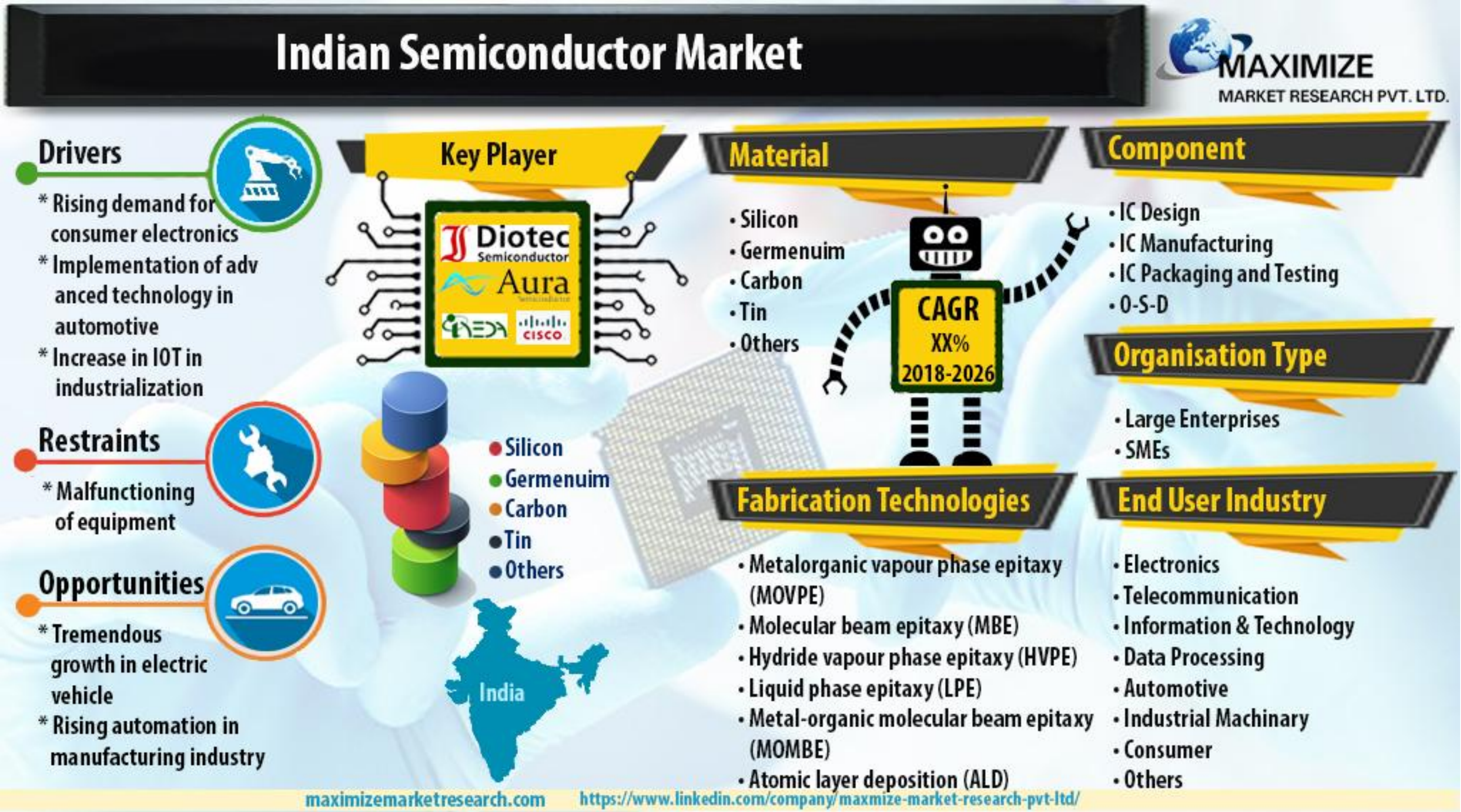


Advanced composites, a significant trend in the materials industry, are engineered materials made from two or more constituent materials with significantly different physical or chemical properties. These composite solutions are known for their exceptional strength-to-weight ratio, corrosion resistance, and durability. Key benefits include enhanced performance, longevity, and lightweight properties, leading to energy efficiency and reduced environmental impact. They find extensive applications across various industries – aerospace for aircraft components, automotive for lightweight and fuel-efficient vehicles, construction for durable structures, and more.



MMR
North America market accounted largest share in the Graphene Electronics Market in 2024.
15.6% CAGR
Graphene Electronics Market to grow at a CAGR of 15.6% during 2024-2032
Graphene Electronics Market
Graphene Electronics Market size in USD Billion (2019-2032)
501.70
1599.96
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
Graphene Electronics Market, by Type in 2024 (Mn)
Graphene supercapacitors
Graphene chips and ICs
Graphene sensors
Graphene transistors
Graphene Electronics Market, by Region In 2024 (%)
Asia Pacific
North America
Europe
Middle East and Africa
South America


MMR
North India Market Accounted largest share in the Market
27.2% CAGR
Global Market to grow at a CAGR of 27.2% during 2024-2030
Indian Semiconductor Market
Indian Semiconductor Market Share, by Region in 2023 (%)
2023
North India
East India
West India
South India
Global Market Size
2023
2030
USD 35.18
USD 189.56
Market Size in Billion
Indian Semiconductor Market, by Application In 2023 (%)
Electronics
Telecommunication
Information & Technology
Data Processing
Automotive
Industrial Machinery
Others Sports & Fitness
Indian Semiconductor Market, by Material in 2023 (Bn)
Others
Tin
Carbon
Geranium
Silicon



The Union Cabinet has approved four new semiconductor projects under the India Semiconductor Mission, boosting the nation's ecosystem. These projects, with an investment of Rs 4,600 crore, include India's first commercial compound fabrication facility and an advanced glass-based substrate packaging unit. The newly approved plants will be located in three states, namely, Odisha, Punjab, and Andhra Pradesh.

Electronic Materials

- The goal of electronic materials is to generate and control the flow of an electrical current.
- Electronic materials include:
  1. Conductors: have low resistance which allows electrical current flow
  2. Insulators: have high resistance which suppresses electrical current flow
  3. Semiconductors: can allow or suppress electrical current flow

Electrical Resistivity and Conductivity of Selected Materials at 293 K

Table 11.1 Electrical Resistivity and Conductivity of Selected Materials at 293 K

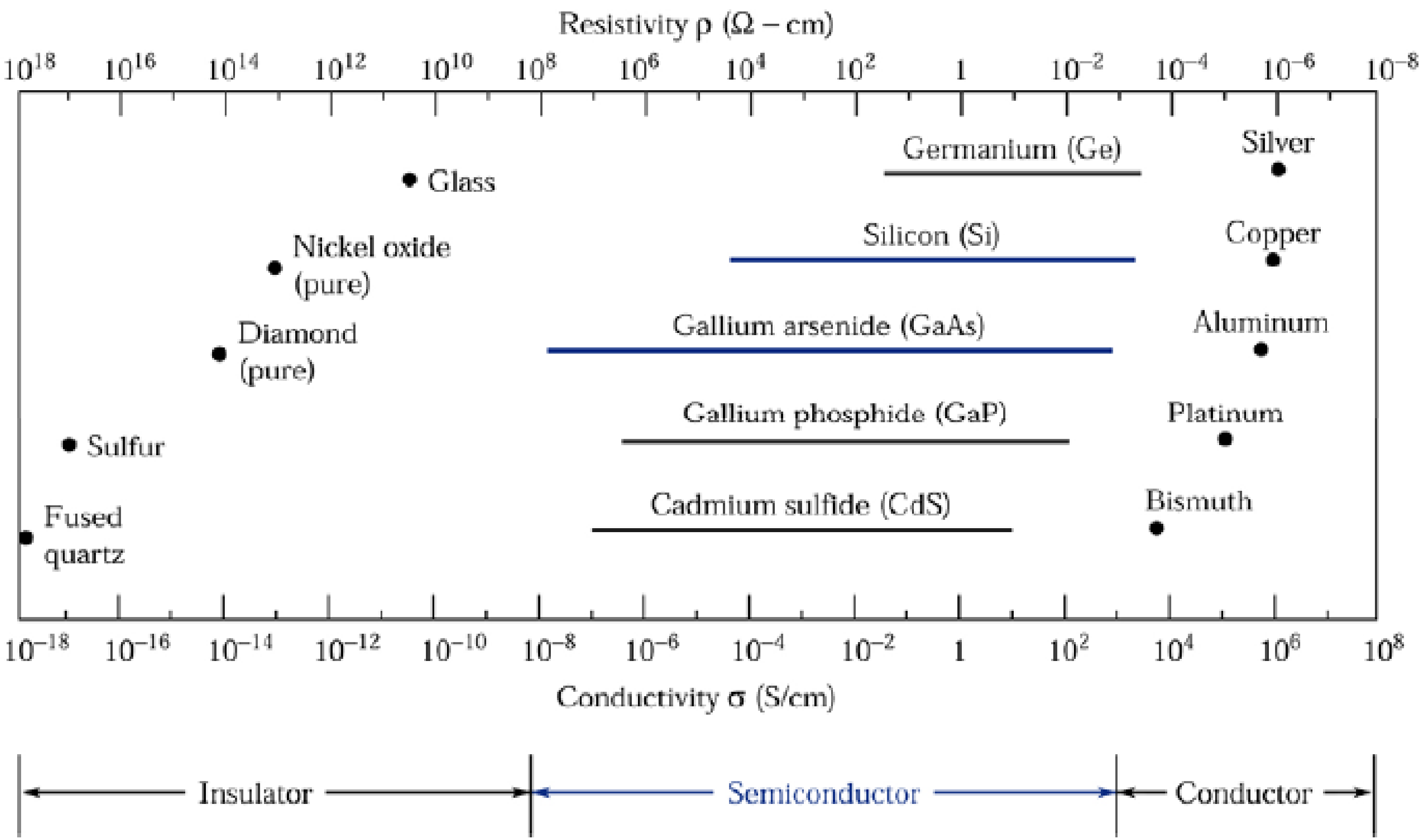
Material	Resistivity ($\Omega \cdot m$)	Conductivity ($\Omega^{-1} \cdot m^{-1}$)
Metals		
Silver	1.59×10^{-8}	6.29×10^{7}
Copper	1.72×10^{-8}	5.81×10^{7}
Gold	2.44×10^{-8}	4.10×10^{7}
Aluminum	2.82×10^{-8}	3.55×10^{7}
Tungsten	5.6×10^{-8}	1.8×10^{7}
Platinum	1.1×10^{-7}	9.1×10^{6}
Lead	2.2×10^{-7}	4.5×10^{6}
Alloys		
Constantan	4.9×10^{-7}	2.0×10^{6}
Nichrome	1.5×10^{-6}	6.7×10^{5}
Semiconductors		
Carbon	3.5×10^{-5}	2.9×10^{4}
Germanium	0.46	2.2
Silicon	640	1.6×10^{-3}
Insulators		
Wood	10^{8}–10^{11}	10^{-8}–10^{-11}
Rubber	10^{13}	10^{-13}
Amber	5×10^{14}	2×10^{-15}
Glass	10^{10}–10^{14}	10^{-10}–10^{-14}
Quartz (fused)	7.5×10^{17}	1.3×10^{-18}

Reviewing the previous table reveals that:

- The electrical conductivity at room temperature is quite different for each of these three kinds of solids
  - **Metals and alloys** have the highest conductivities
  - followed by **semiconductors**
  - and then by **insulators**

Semiconductor material –

conductivities for insulators, semiconductors, and conductors.



Semiconductor Conduction

- The **free-electron** model from Physics does not apply to semiconductors and insulators, since these materials simply lack enough free electrons to conduct in a free-electron mode.

  There is a different conduction mechanism for semiconductors than for normal conductors.

Resistivity vs. Temperature

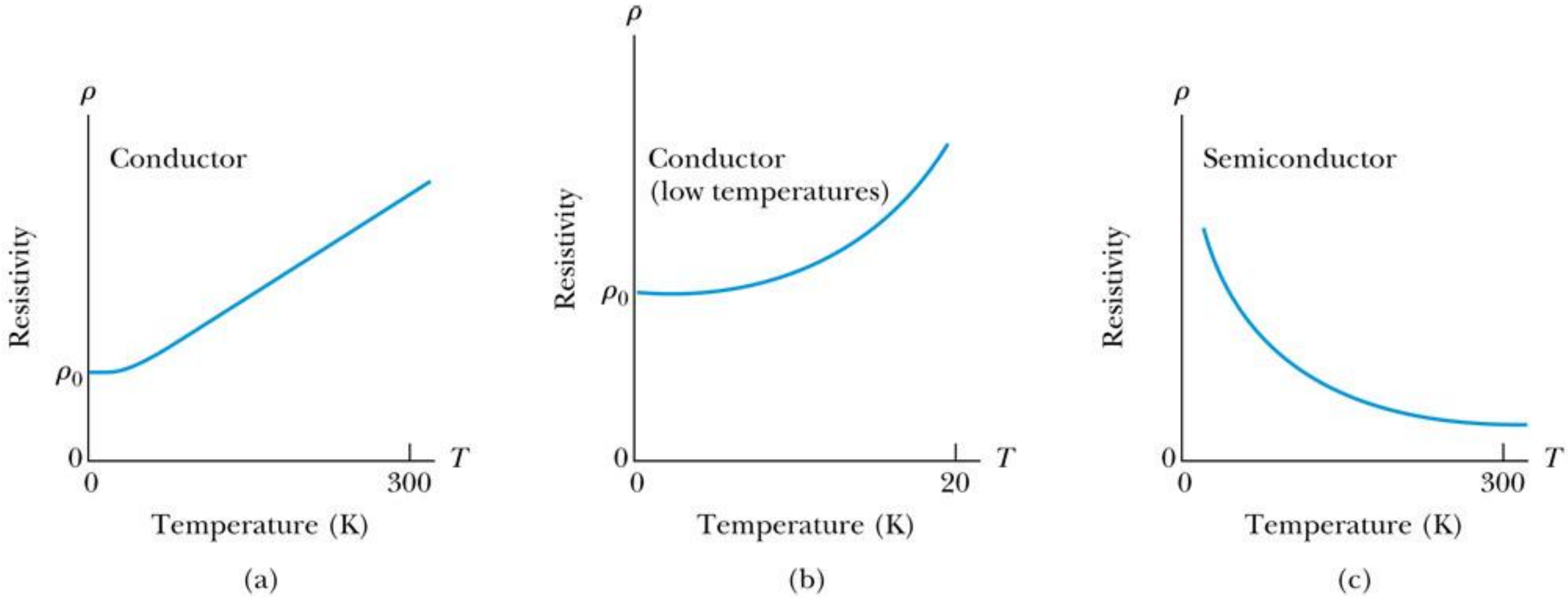


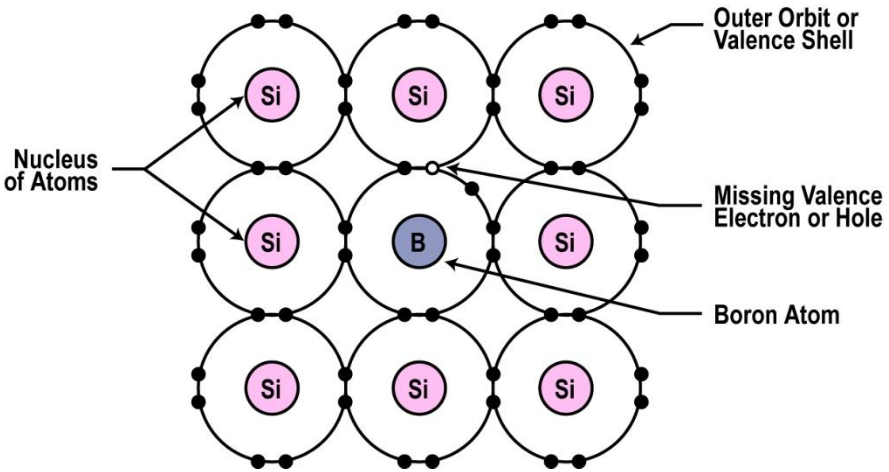
Figure 11.1: (a) Resistivity versus temperature for a typical conductor. Notice the linear rise in resistivity with increasing temperature at all but very low temperatures. (b) Resistivity versus temperature for a typical conductor at very low temperatures. Notice that the curve flattens and approaches a nonzero resistance as $T \to 0$. (c) Resistivity versus temperature for a typical semiconductor. The resistivity increases dramatically as $T \to 0$.

Resistance Effects of Doping

- If you use lots of arsenic atoms for doping, there will be lots of extra electrons so the resistance of the material will be low and current will flow freely.
- If you use only a few boron atoms, there will be fewer free electrons so the resistance will be high and less current will flow.
- By controlling the doping amount, virtually any resistance can be achieved.

Another Way to Dope

- You can also dope a semiconductor material with an atom such as boron that has only 3 valence electrons.
- The 3 electrons in the outer orbit do form covalent bonds with its neighboring semiconductor atoms as before. But one electron is missing from the bond.
- This place where a fourth electron should be is referred to as a hole.
- The hole assumes a positive charge so it can attract electrons from some other source.
- Holes become a type of current carrier like the electron to support current flow.

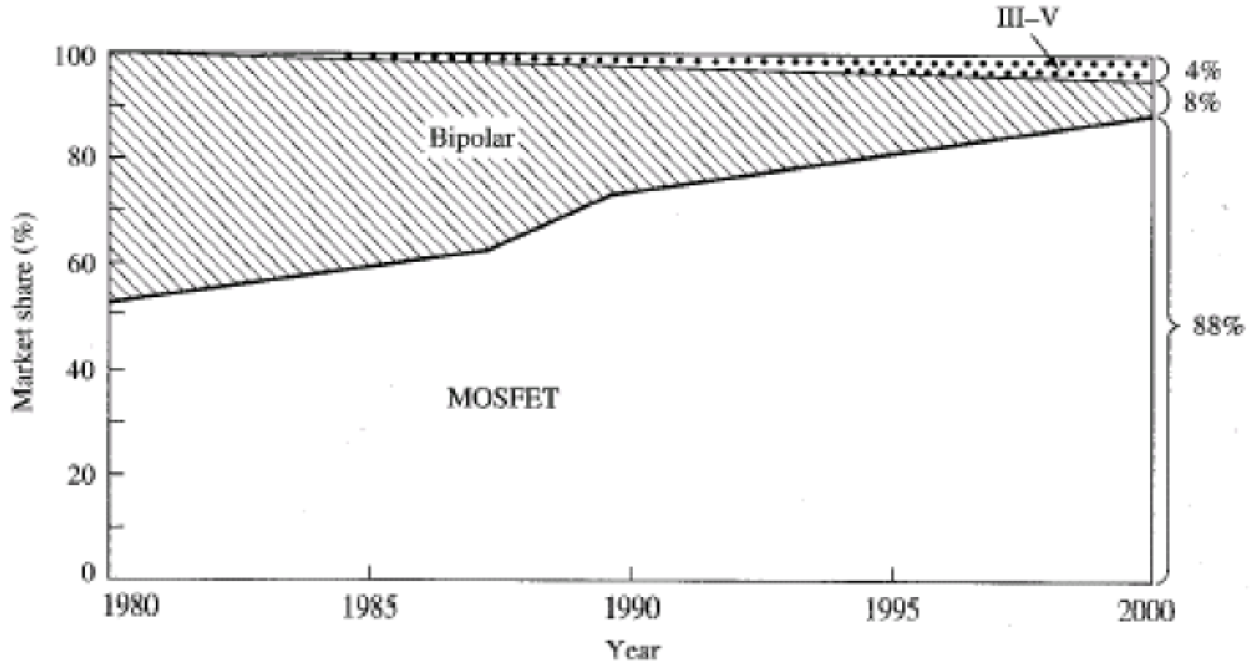


1.4 Electronic Materials

More than 95% of the electronic devices are based on silicon (Si) technology. Therefore, silicon is the most important material in semiconductor industry. Most of the electronic products like microprocessors or memory products are based on silicon technology. Alternative materials like gallium arsenide or germanium are used for specific applications, like light emitting diodes or ultra high speed electronics.

Nowadays the most important electronic device is the Metal oxide semiconductor field effect transistor (MOSFET). The MOSFET is closely related to Digital Electronics. If it comes to the realization of digital electronics the MOS transistor is the electronic device of choice. Bipolar transistors are mainly used in the area of analog electronics. Throughout the last 20 years we have seen a trend from analog to digital electronics. However, there is still (and will be) a need for analog electronics.

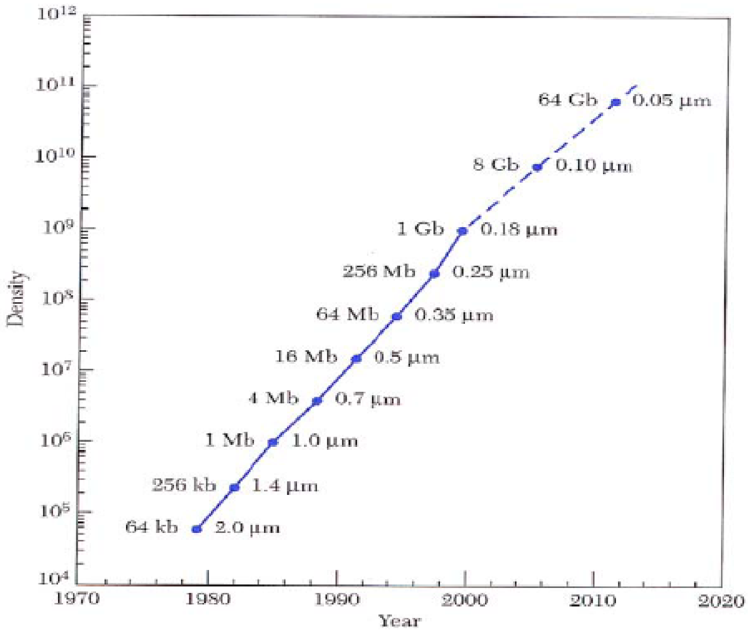
1.4 Electronic Materials

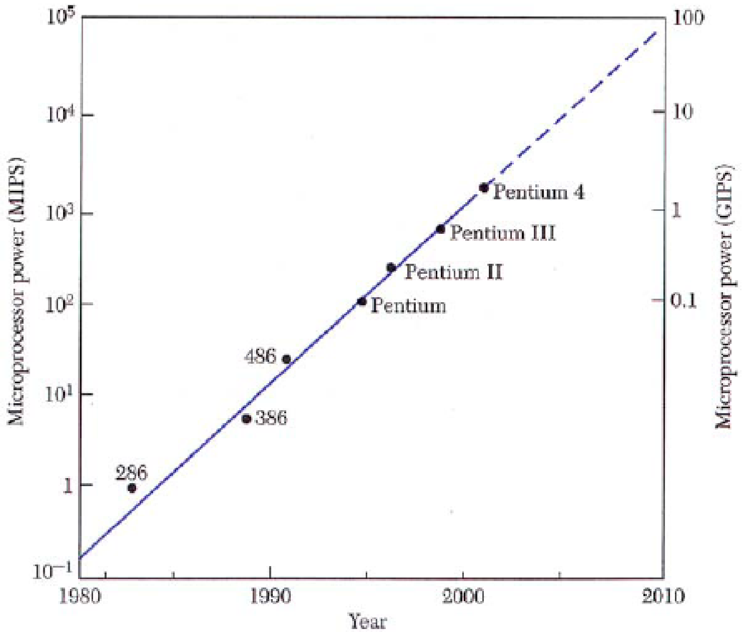


Market share of different electronic devices.

Interestingly the first transistors and the first integrated circuits were bipolar devices. Initially MOS technology had only an incremental advantage over bipolar technology. III-V technology (including materials like gallium arsenide) is of main interest in the area of optoelectronic devices like light emitting diodes.

1.5 The silicon roadmap



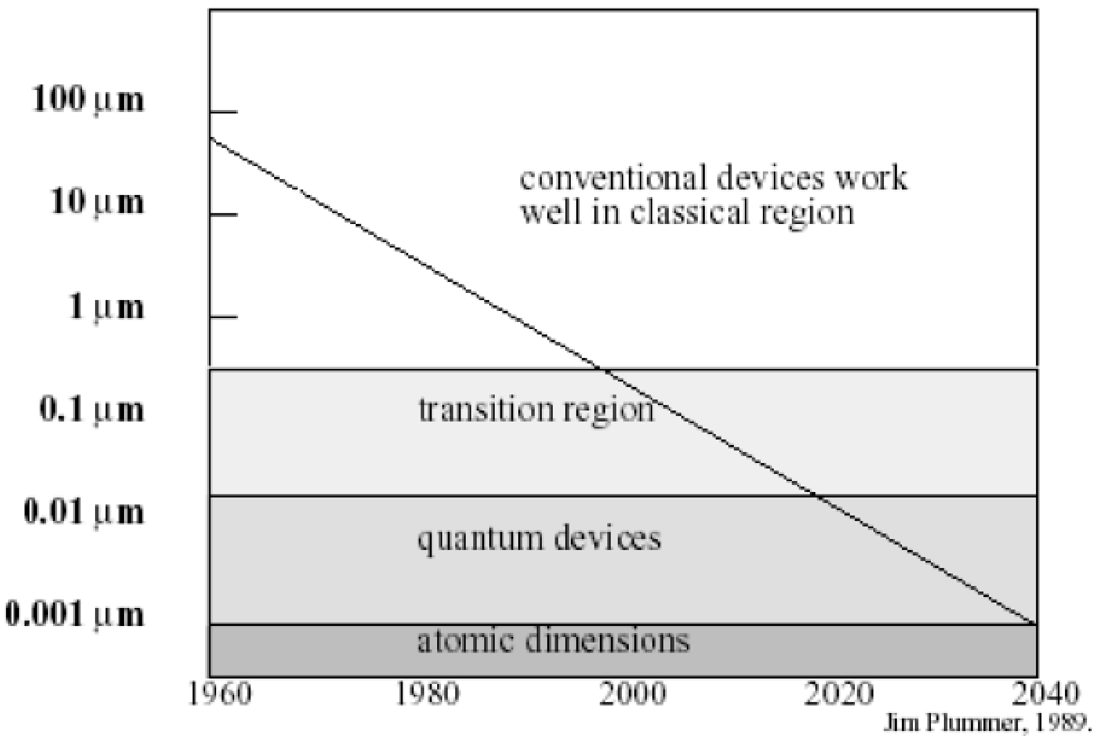


Exponential increase of the memory size (dyanmic random access memory, DRAM) and microprocessor power over time. The curves are kown as „Moore's law".

Ref.: M.S. Sze, Semiconductor Devices

1.6 What's next? (Predictions and Outlooks)

What is beyond CMOS (Complementary metal oxide semiconductor) and MOSFET (metal oxide semiconductor field effect transistors)!

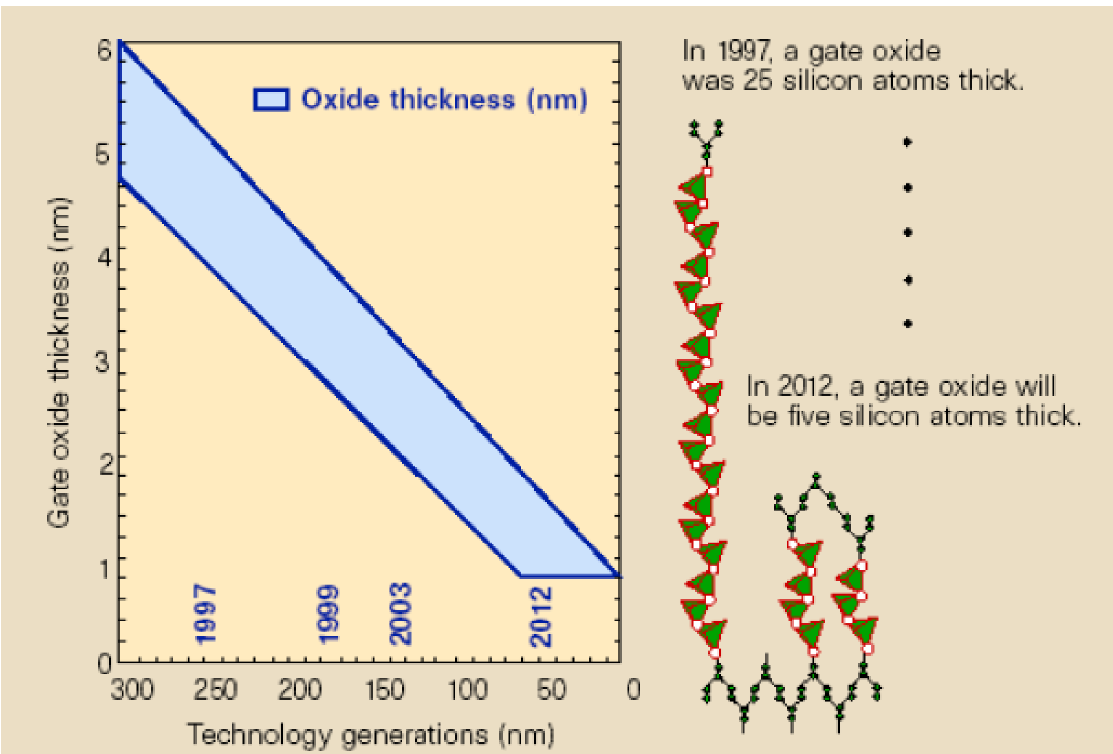


Devices are getting smaller and smaller. Will electronic devices reach quantum or even atomic dimensions?

What principles will they operate on?

1.6.1 Silicon electronics

What is beyond CMOS (Complementary metal oxide semiconductor) and MOSFET (metal oxide semiconductor field effect transistors)!



Gate oxide thickness of metal oxide semi-conductor field effect transistors.

1.6.2 Nanotechnology!

Increasing the control over material structures of nanoscale size 0.1nm to100nm.

Top-down Approach towards Nanotechnology:
Fabrication and realization of electronic devices from macroscopic down to nanoscopic scale by a step-by-step improvement of existing technologies: e.g. lithography in microelectronics.

Bottom-up Approach towards Nanotechnology:
Bottom-up refers to synthesis from individual molecules or atoms

The following mechanism are used to build device structures:
- Surface tension, strain, hydrophilic/hydrophobic
- Selective growth
- Supramolecular chemistry
- Fluidic self-assembly

While traditional chemistry focuses on covalent bond, superamolecular chemistry examines the weaker and reversible noncovalent interaction like hydrogen bonding, hydrophobic forces, van der waals forces, pi-pi interaction etc…

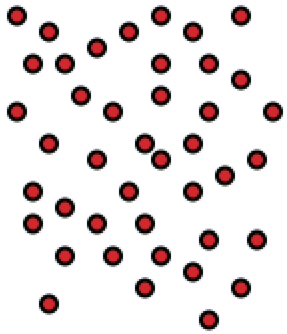
Is a new technique, which makes possible the integration of devices fabricated using dissimilar materials and processes

Periodic Table of the Elements 2005

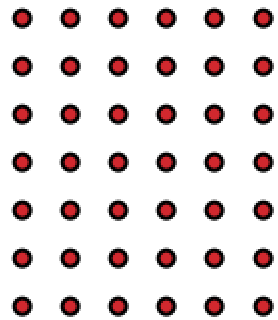
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H 1.01																	2 He 4.00
3 Li 6.94	4 Be 9.01											5 B 10.81	6 C 12.01	7 N 14.01	8 O 15.99	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 25.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.87	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.41	31 Ga 69.72	32 Ge 72.64	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.90	54 Xe 131.29
55 Cs 132.91	56 Ba 137.33	57 La 138.91	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (264)	108 Hs (270)	109 Mt (268)	110 Ds (281)	111 Rg (272)							
				58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.97	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
				90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

Molecular Research Institute

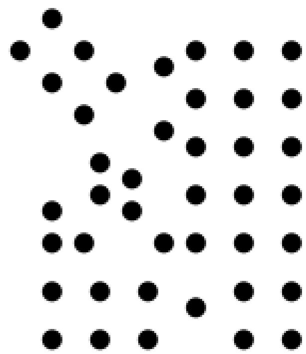
Classification of Materials



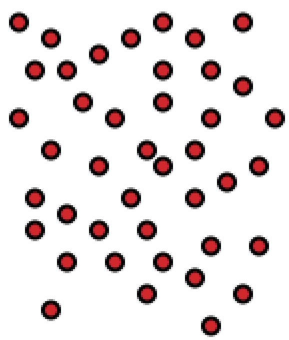
AMORPHOUS STATE



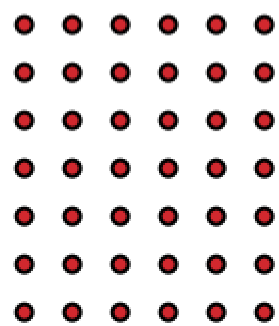
CRYSTALLINE STATE



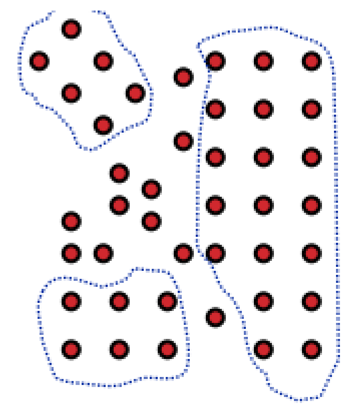
POLYCRYSTALLINE STATE



AMORPHOUS STATE



CRYSTALLINE STATE



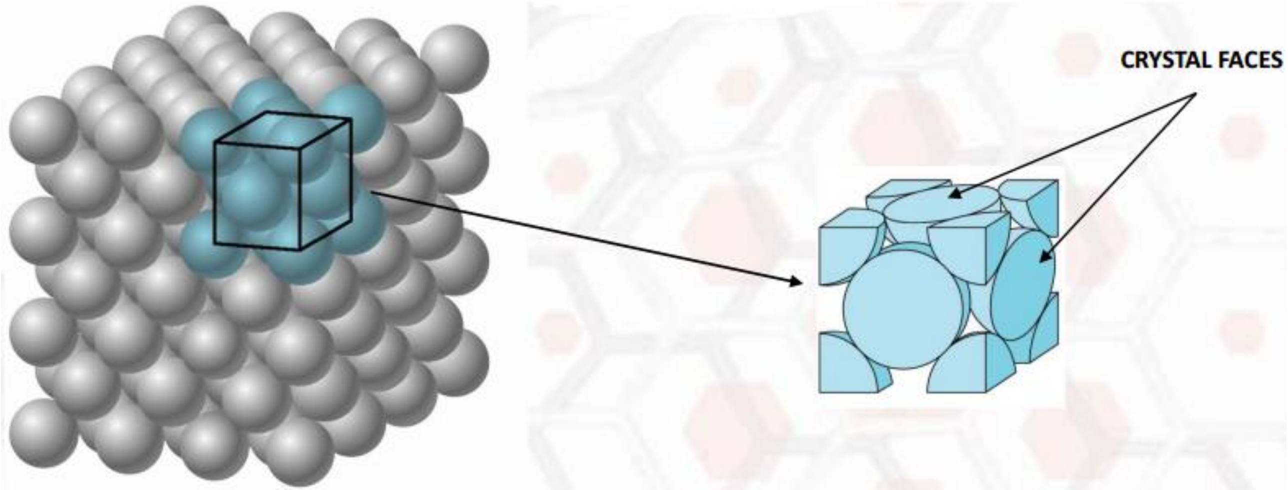
POLYCRYSTALLINE STATE

Materials and Packing

- Crystalline materials...
  - atoms pack in periodic, 3D arrays .
  - typical of: -metals ,many ceramics ,some polymers
- Non-crystalline materials...
  - atoms have no periodic packing
  - occurs for: complex structures.

  "Amorphous "= Non crystalline

Crystal



- A **crystal** or **crystalline solid** is a solid material whose constituents (such as atoms, molecules, or ions) are arranged in a highly ordered microscopic structure, forming a crystal lattice that extends in all directions.

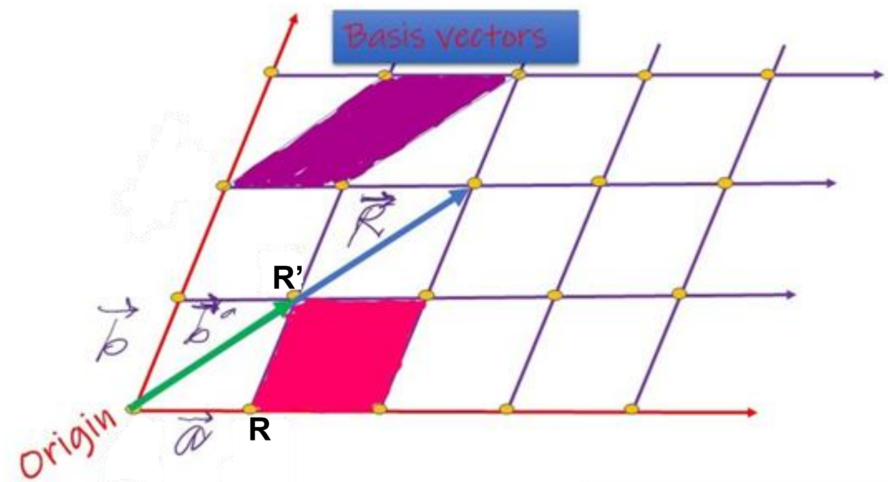
"A CRYSTAL is any solid material in which the component atoms are arranged in a definite pattern"

Crystal Structure:Translation Vector

- A crystal lattice can always be constructed by the repetition of a fundamental set of translational vectors in real space a, b, and c, i.e., any point in the lattice can be written as:

$$T = n_1 a + n_2 b + n_3 c$$

- Such a lattice is called a **Space/Bravais lattice**. The translational vectors, a, b, and c are the primitive vectors, called as fundamental translational vector/crystal axes or basis vector.



Concept of Reciprocal Space:

Real Space

- **Description:** The physical, tangible world we experience.
- **Dimensions:** Measured in standard units of length (e.g., meters, angstroms).
- **Representation:** Describes the physical arrangement of atoms in a crystal lattice.
- **Example:** The arrangement of atoms in a solid crystal.

Reciprocal Space

- **Description:** A mathematical or abstract space.
- **Dimensions:** Measured in inverse units of length, such as 1/length or wavenumber (k-space).
- **Representation:** Represents spatial frequencies and is the dual of real space.
- **Purpose:** Used to understand wave phenomena like diffraction, where it provides information about the momentum difference between waves.

Concept of Reciprocal Space:

Key Differences & Relationship

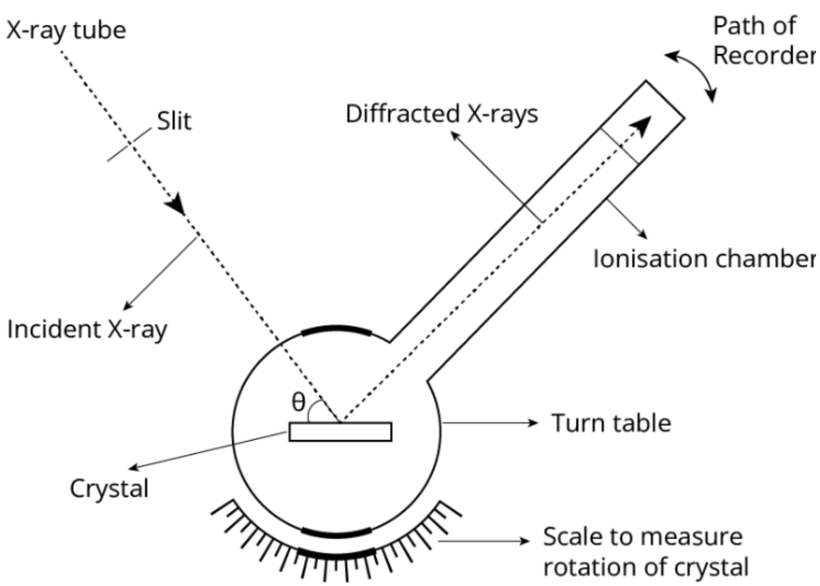
•**Inverse Relationship:** Reciprocal space can be thought of as a Fourier transform of real space.

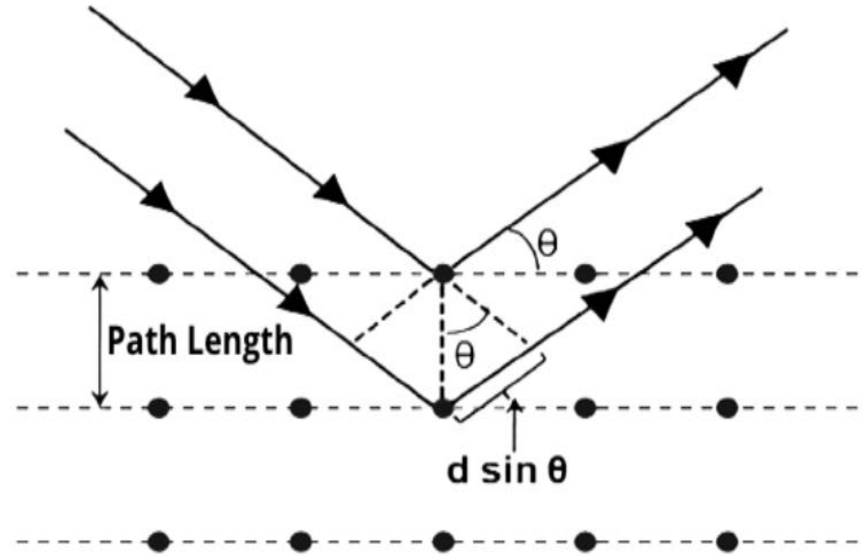
•**Geometric Properties:**

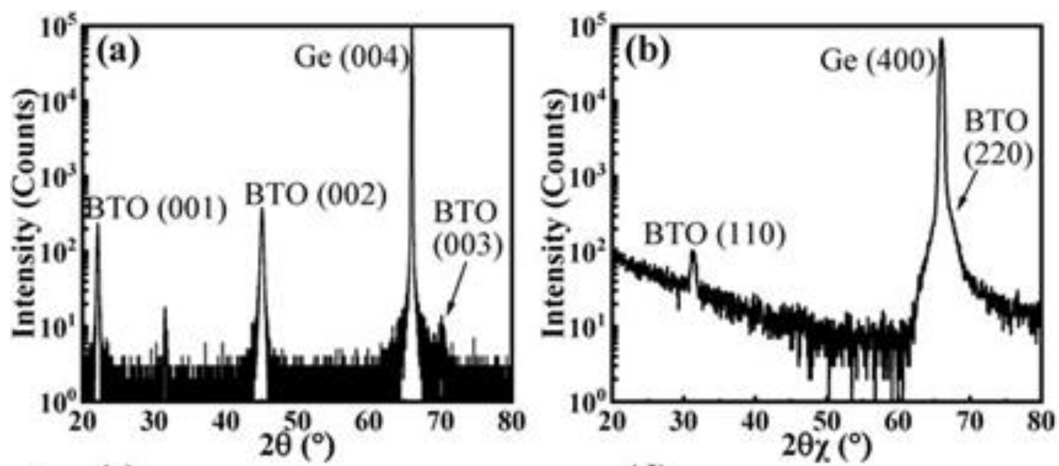
- A set of planes in real space is represented by a single point in reciprocal space.
- The Bragg planes in real space are related to the reciprocal lattice vectors.
- The spacing between planes in real space becomes the magnitude of a reciprocal lattice vector, and vice versa.

A **Bragg plane** is a conceptual crystallographic plane within a crystal structure that acts as a mirror, reflecting X-rays when they satisfy Bragg's Law ($n\lambda = 2d \sin\Theta$). When X-rays are diffracted by a crystal, the observed diffraction pattern (the Bragg pattern) results from the constructive interference of X-rays scattered by these planes, with strong reflections occurring at specific angles where the path difference between waves from adjacent planes is an integer multiple of the X-ray wavelength.
This concept is crucial for understanding Brillouin zones, as the boundaries of Brillouin zones are formed by intersecting Bragg planes.

Concept of Reciprocal Space:







Concept of Reciprocal Space:

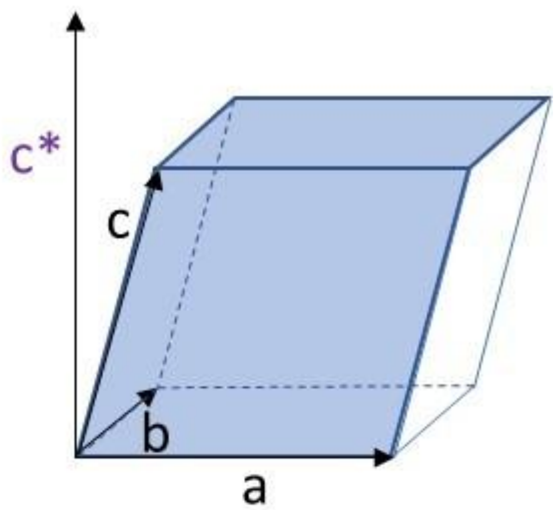
When the crystal is the image in real space, the diffraction pattern is the image of crystal lattice in reciprocal space.

For diffraction, the reciprocal lattice basis vector is perpendicular to a set of crystal planes that are set apart by inverse of the length of the real-space lattice basis vector.

$$a^* = \frac{b \times c}{a.(b \times c)}$$

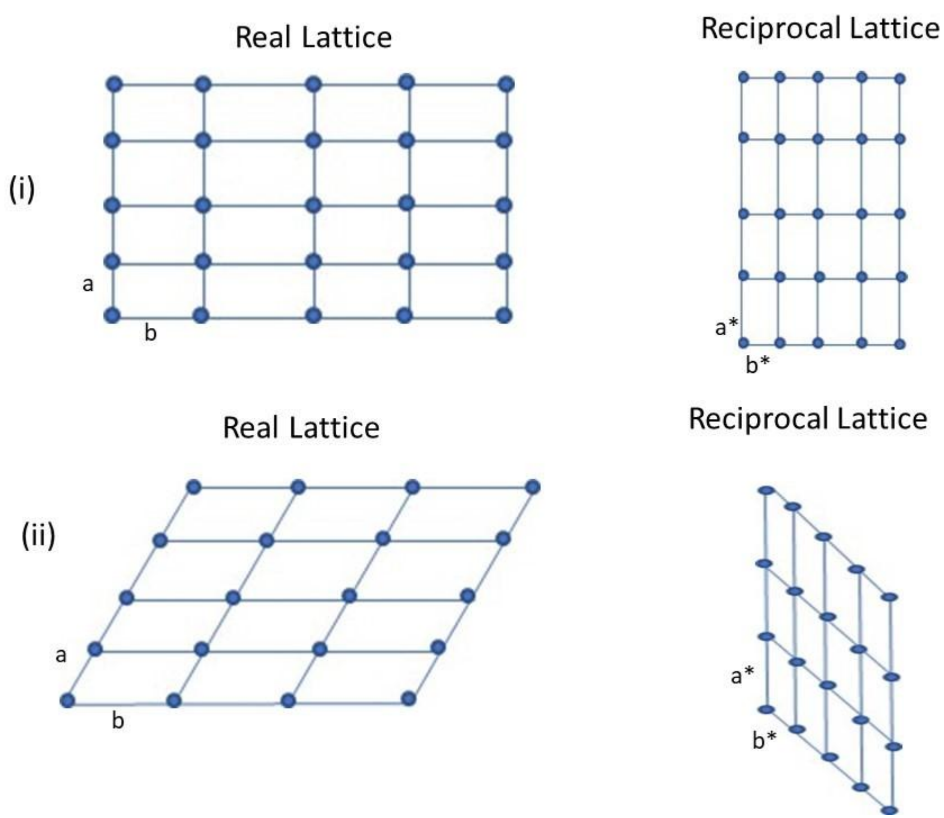
$$b^* = \frac{c \times a}{a.(b \times c)}$$

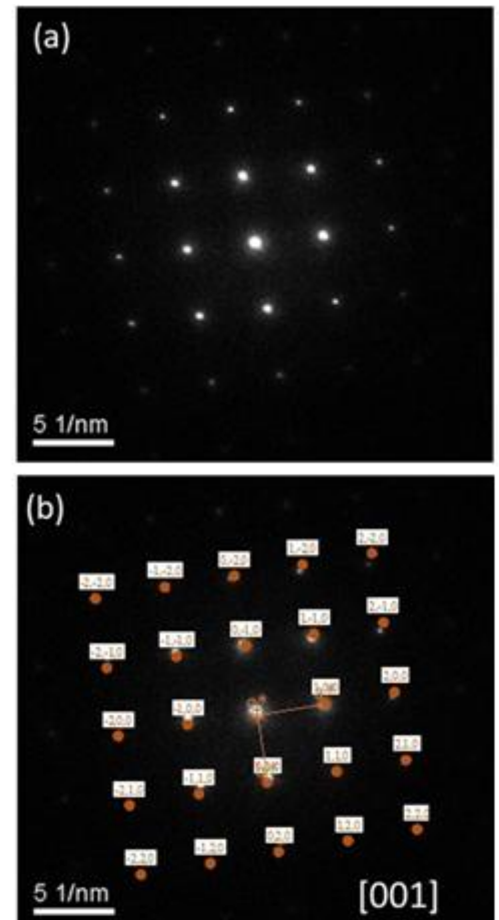
$$c^* = \frac{a \times b}{a.(b \times c)}$$



Concept of Reciprocal Space:

The real-lattice translation to the reciprocal lattice is shown below. (i) Observe that rectangular lattice translates to its inverse spacing in the reciprocal space. Also, in (ii) the parallelogram lattice translates to the reciprocal lattice, where the new vectors are perpendicular to the other real lattice vector (i.e. a* is perpendicular to b, and b* is perpendicular to a).

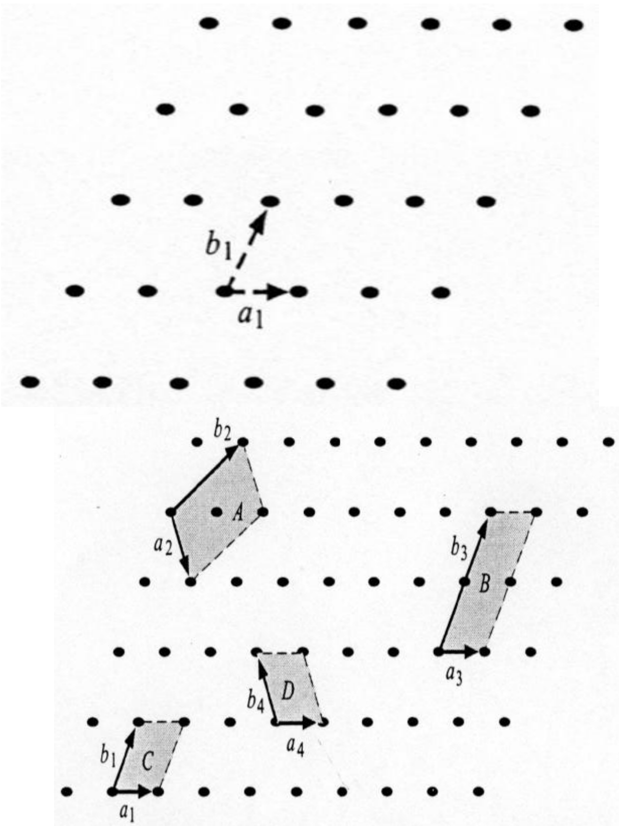


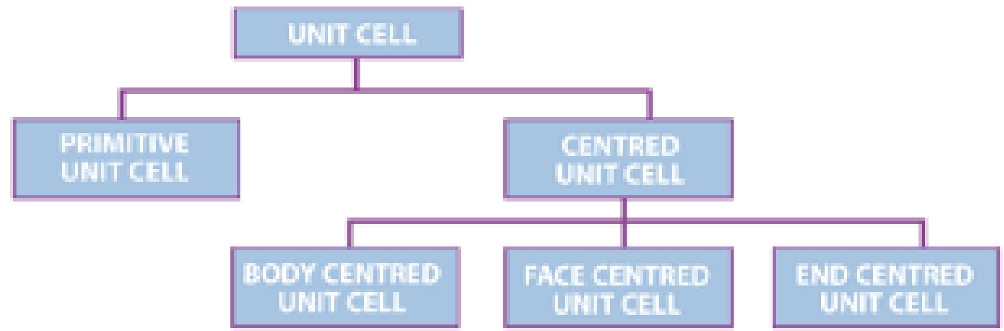


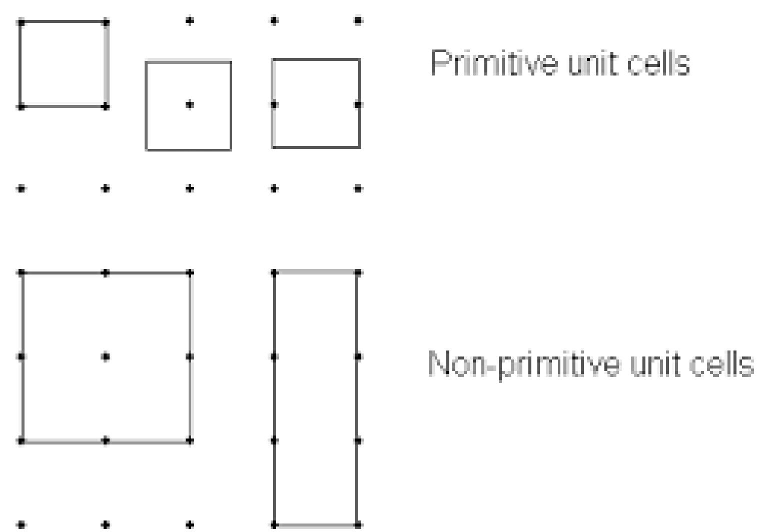
Concepts of Crystal Structure:

Because a three-dimensional lattice is a periodic repetition of a group of atoms, we need consider only a fundamental unit that is being repeated.

A **unit cell** is a small volume of the crystal that can be used to reproduce the entire crystal. A unit cell is not a unique entity. There exist various possible unit cells.



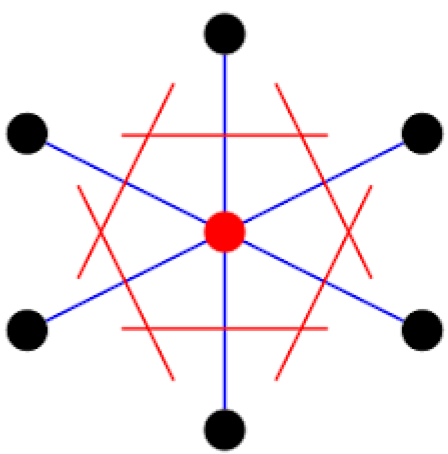


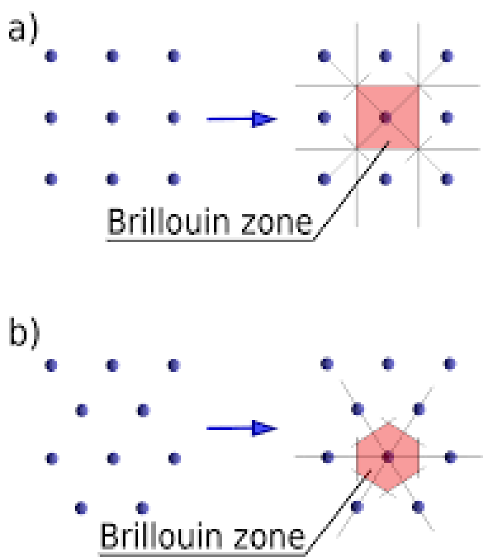


Concepts of Crystal Structure:

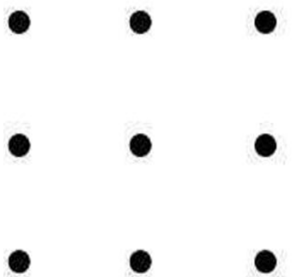
A Wigner–Seitz cell is a type of primitive cell in crystallography, named after Eugene Wigner and Frederick Seitz, which represents the smallest region around a lattice point that is closer to that point than any other.
It's constructed by defining the region closer to one lattice point than any other, and it serves as a representative volume for understanding the periodic properties of a crystal.

The Wigner–Seitz cell in the reciprocal space is known as the first Brillouin zone.

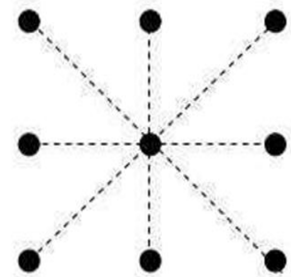




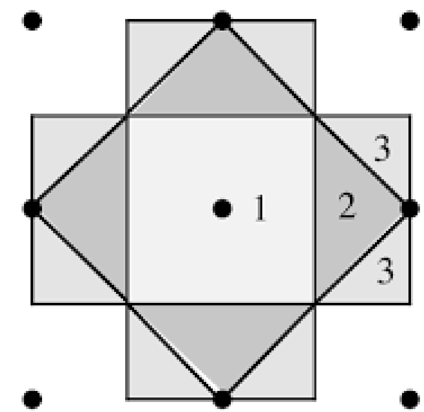
Concepts of Crystal Structure:

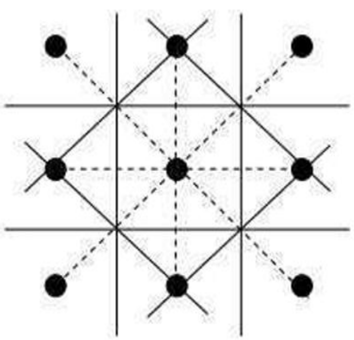


a) Two dimensional square lattice

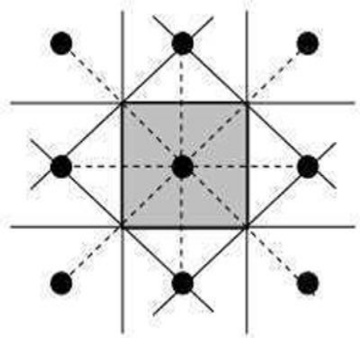


b) Draw lines from a given lattice point to all of its nearest neighbors

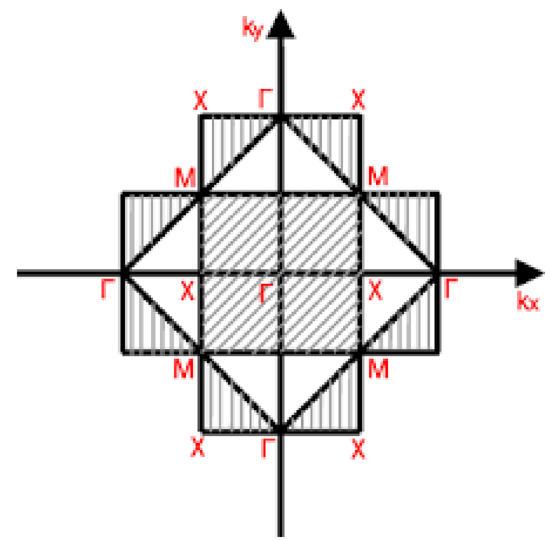




c) Draw perpendicular bisectors to the lines joining the point to its nearest neighbors

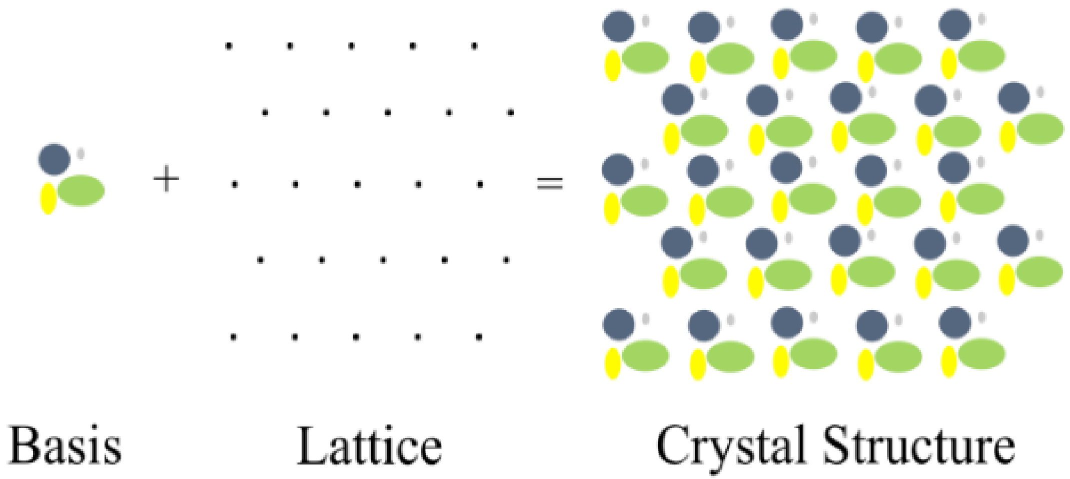


d) The Wigner-Seitz cell is identified as the innermost region bounded by the perpendicular bisectors. It is shown in the figure as the shaded region.



Concepts of Crystal Structure: Basis and Lattice

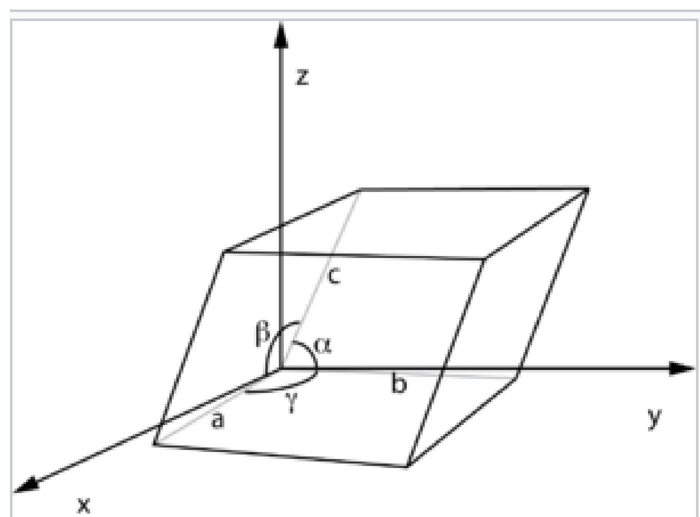
Lattice + Basis=Crystal structure



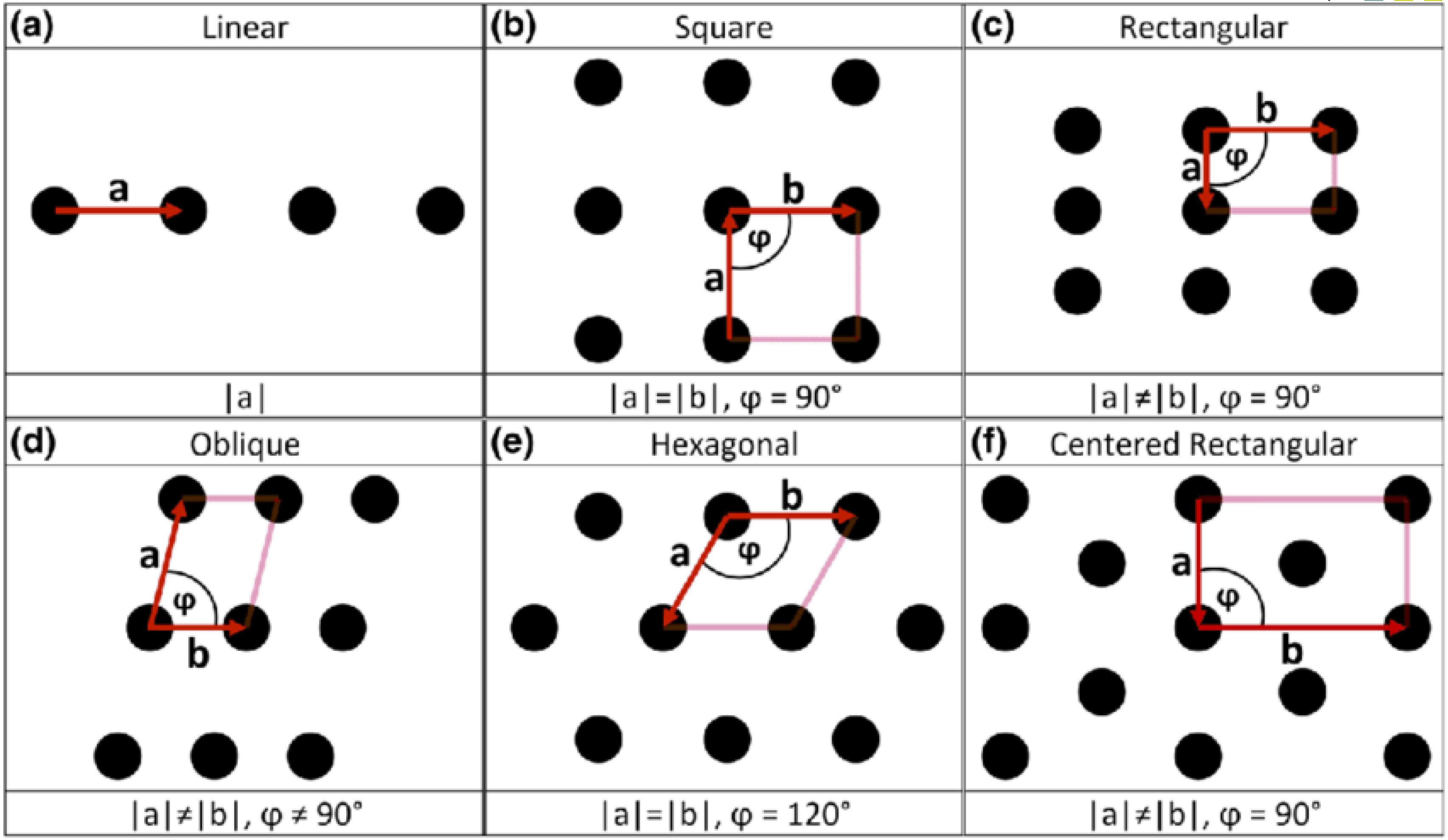
- Mathematical point of view, lattice is actually specific coordinates in space. The reason why these atoms are arranged regularly is because of they sit on the lattice.

Concepts of Crystal Structure: Lattice Parameters

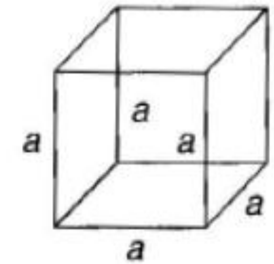
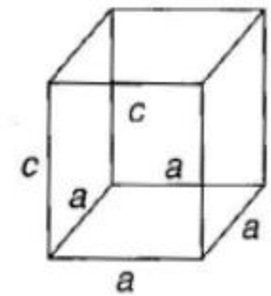
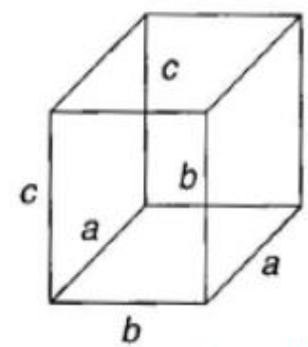
- **lattice constant**, or **lattice parameter**, refers to the physical dimension of unit cells in a crystal lattice.
- full set of lattice parameters consist of the three lattice constants (a,b,c) and the three angles (α, β,γ) between them.

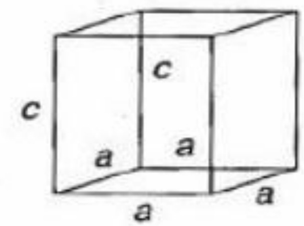
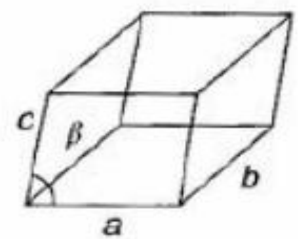
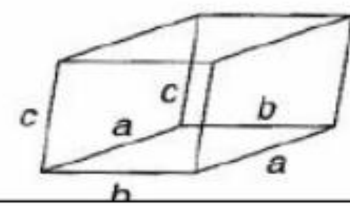


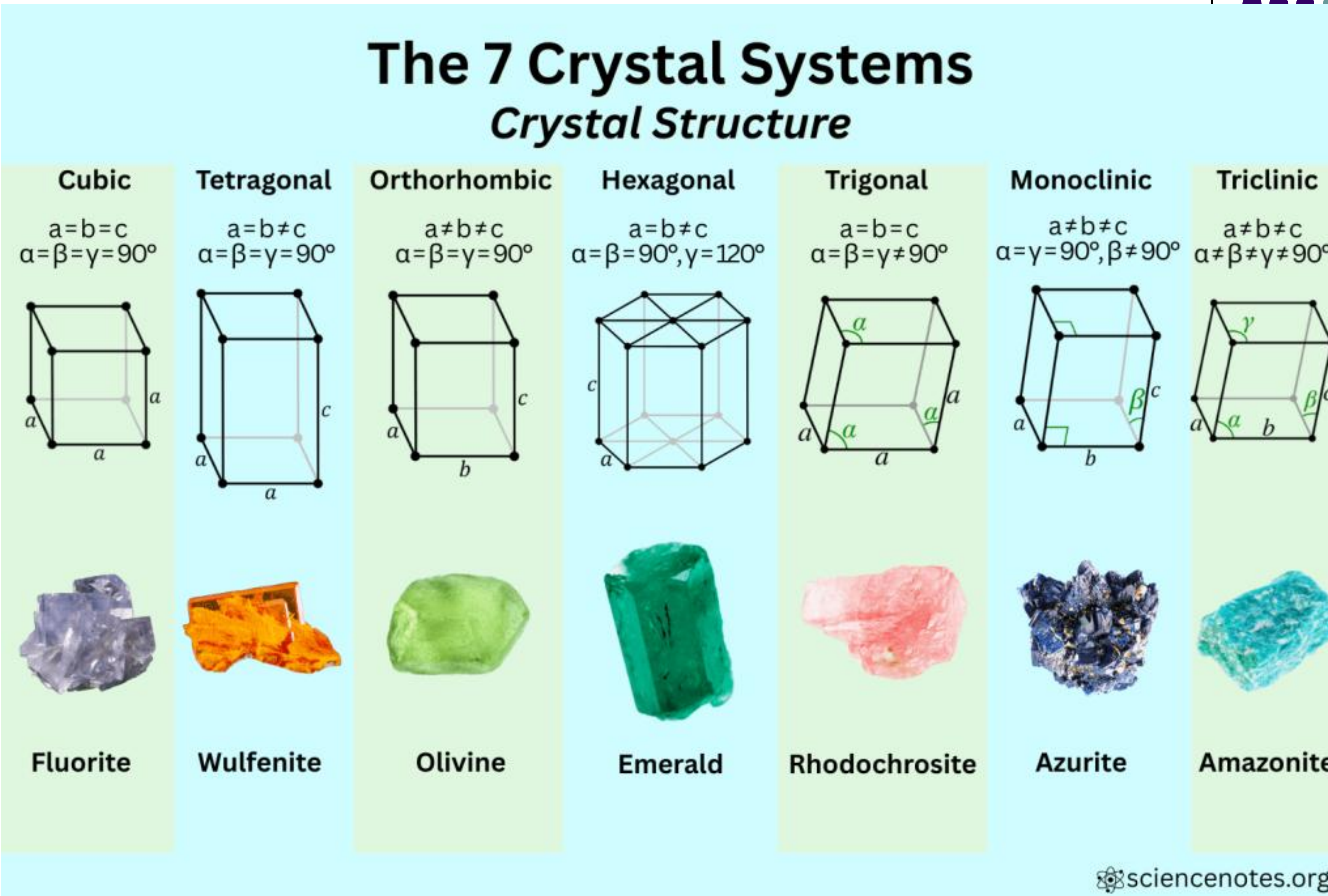
Crystallography in 1D and 2D



Crystallography in 3D

System	Lattice constants and angles	Unit cell geometry
Cubic	$a = b = c, \alpha = \beta = \gamma = 90°$	
Tetragonal	$a = b \neq c, \alpha = \beta = \gamma = 90°$	
Orthorhombic	$a \neq b \neq c, \alpha = \beta = \gamma = 90°$	

System	Axial lengths and angles	Unit cell geometry
Rhombohedral	$a = b = c, \alpha = \beta = \gamma \neq 90°$	
Hexagonal	$a = b \neq c, \alpha = \beta = 90°, \gamma = 120°$	
Monoclinic	$a \neq b \neq c, \alpha = \gamma = 90°, \neq \beta$	
Triclinic	$a \neq b \neq c, \alpha \neq \beta \neq \gamma \neq 90°$	


The 7 Crystal Systems
Crystal Structure
Cubic
a=b=c
α=β=γ=90°
Tetragonal
a=b≠c
α=β=γ=90°
Orthorhombic
a≠b≠c
α=β=γ=90°
Hexagonal
a=b≠c
α=β=90°,γ=120°
Trigonal
a=b=c
α=β=γ≠90°
Monoclinic
a≠b≠c
α=γ=90°,β≠90°
Triclinic
a≠b≠c
α≠β≠γ≠90°
Fluorite
Wulfenite
Olivine
Emerald
Rhodochrosite
Azurite
Amazonite
sciencenotes.org

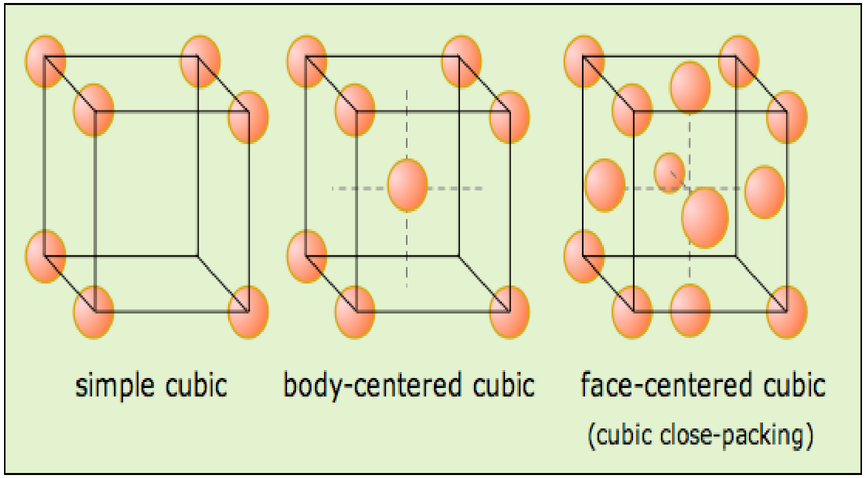
Unit cells

- Primitive unit cell:

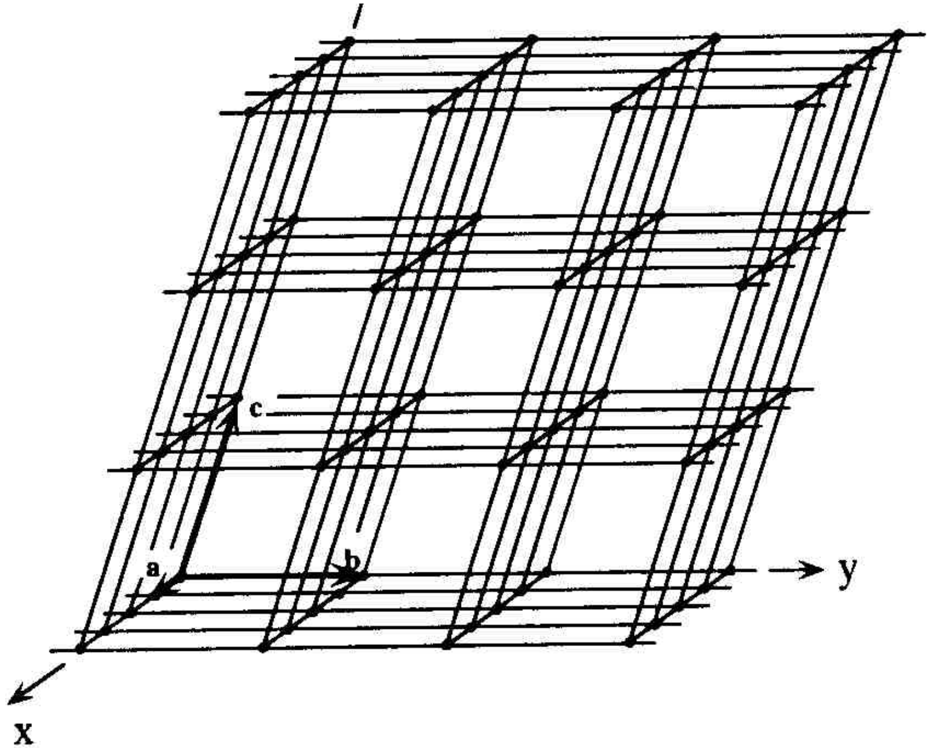
  When atoms in unit cell are present only at the corners

- Centered Unit Cells:

  When atoms are present at other positions in addition to corners in a unit cell

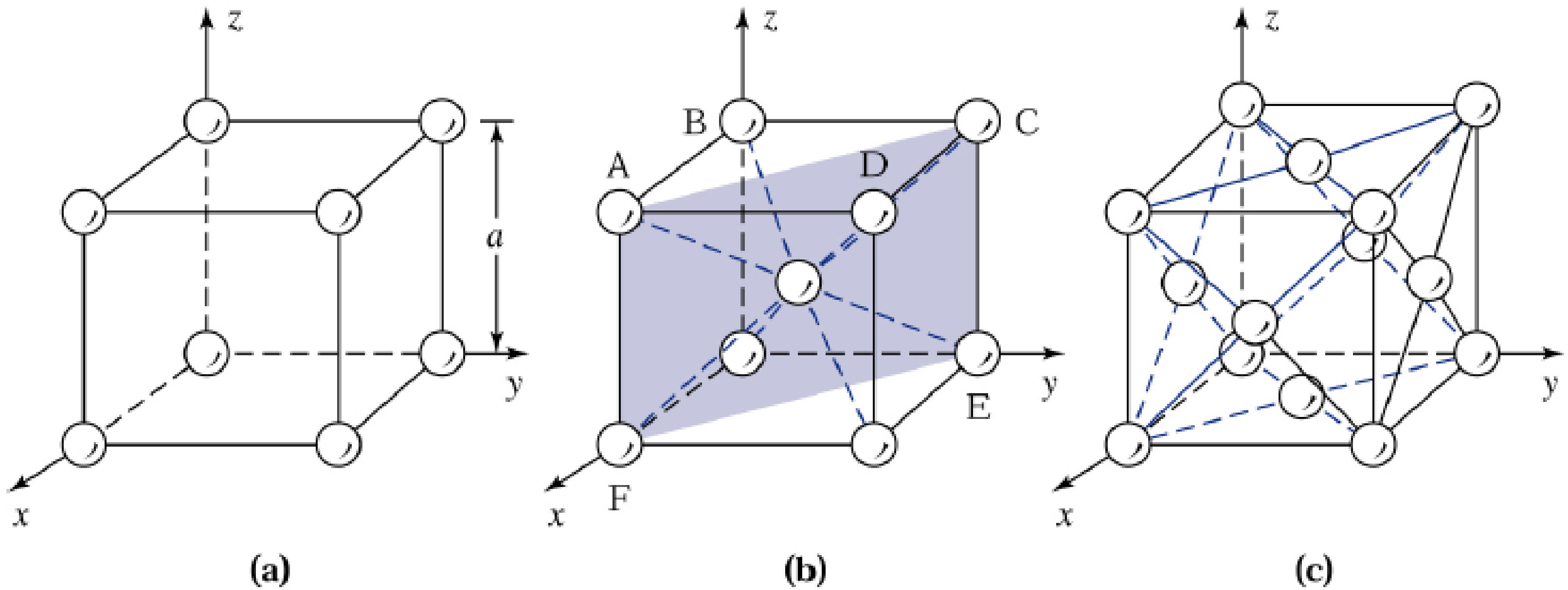


A crystal lattice is a 3-D stack of unit cells



Crystal lattice is an imaginative grid system in three dimensions in which every point (or node) has an environment that is identical to that of any other point or node.

Examples of Some Basic Crystal Structures



(*a*) Simple cubic. **(*b*) Body-centered cubic.** **(*c*) Face-centered cubic.**

For these structures, we can choose three vectors **a**, **b**, and **c** that are perpendicular to each other and equal in length.
The sc structure has an atom located at each corner. The bcc structure has additional atom at the center of the cube. The fcc structure has additional atoms on each face plane.