INTRODUÇÃO A CIÊNCIA DOS MATERIAIS

seminários: quintas-feiras (13h30min às 15h30min)

exercícios e atendimento (combinaremos depois)

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Bibliografia Principal

•HUMMEL, Rolf. E., Understanding Materials Science 2a ed., New York, Springer Verlag, 2004, ISBN: 0-387-20939-5

★CALLISTER JR., WILLIAM D., Ciência e Engenharia dos Materiais: Uma Introdução, 1a ed., Rio de Janeiro, LTC, 2002, ISBN: 85-216-2188-5

Bibliografia Auxiliar

•VAN VLACK, LAWRENCE H., Princípios de Ciência e Tecnologia de Materiais, 1a ed., São Paulo, Editora Campus, 1994, ISBN: 85-700-1480-5

•WHITE, Mary A., Properties of Materials, 1a ed., New York, Oxford University Press, 1999, ISBN: 0-19-511331-4

•CALLISTER JR., WILLIAM D., Fundamentos da Ciência e Engenharia dos Materiais, 2a ed., Rio de Janeiro, LTC, 2006, ISBN: 85-216-1515-9

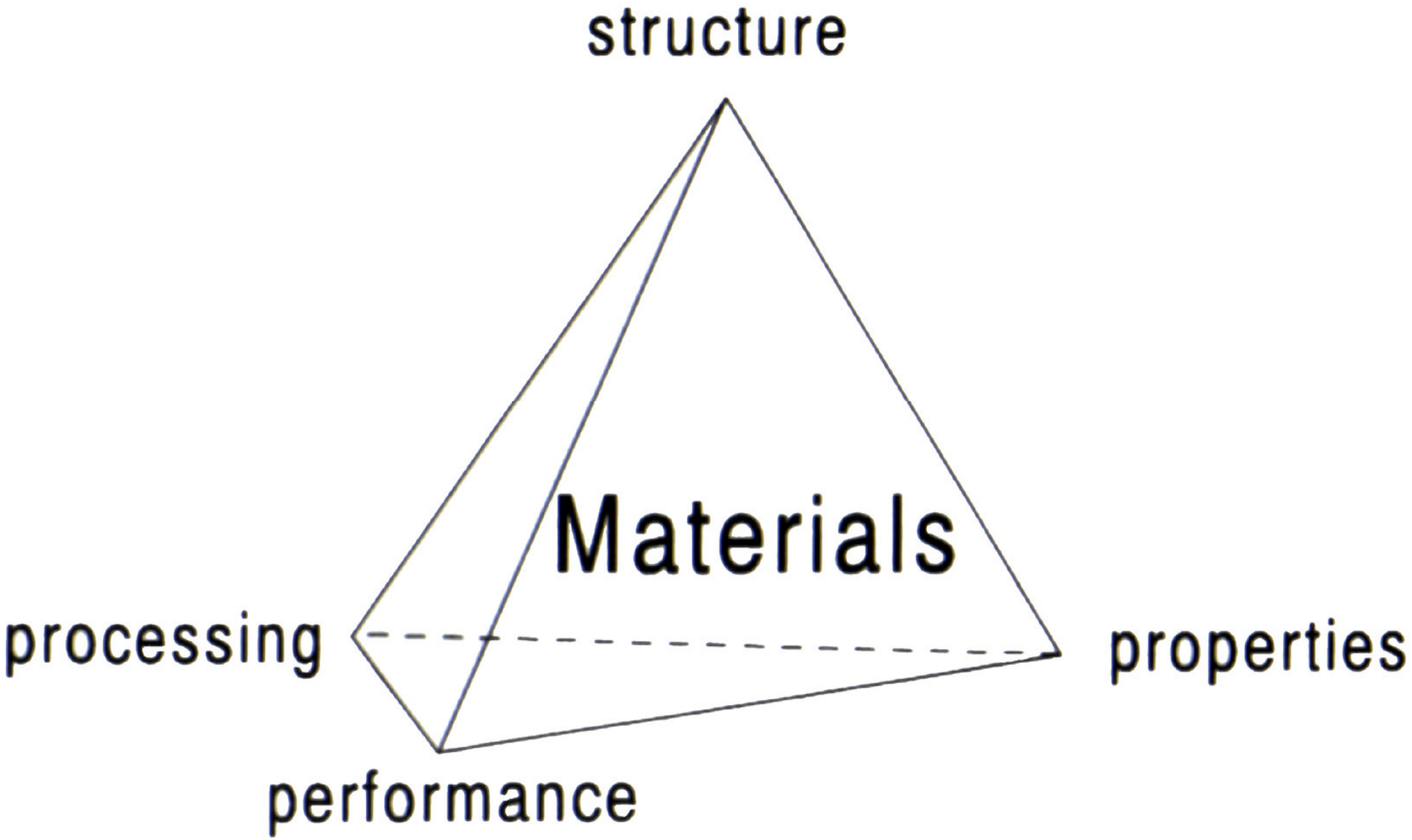


FIGURE 1.1 Materials science is the investigation of the relationships among structure, properties, processing, and performance of materials. (Mary Anne White. *Properties of Materials*.)

CHAPTER 1: MATERIALS SCIENCE & ENGINEERING

Materials are...

engineered structures...not blackboxes!

Structure...has many dimensions...

Structural feature	Dimension (m)
atomic bonding	$< 10^{-10}$
missing/extra atoms	10^{-10}
crystals (ordered atoms)	10^{-8}-10^{-1}
second phase particles	10^{-8}-10^{-4}
crystal texturing	$> 10^{-6}$

SUMMARY

Course Goals:

- **Use the right material for the job.**
- **Understand the relation between properties, structure, and processing.**
- **Recognize new design opportunities offered by materials selection.**

CHAPTER 2:
BONDING AND PROPERTIES

- **What promotes bonding?**
- **What types of bonds are there?**
- **What properties are inferred from bonding?**

SUMMARY: BONDING

Type	Bond Energy	Comments
Ionic	Large!	Nondirectional (ceramics)
Covalent	Variable large-Diamond small-Bismuth	Directional semiconductors, ceramics polymer chains)
Metallic	Variable large-Tungsten small-Mercury	Nondirectional (metals)
Secondary	smallest	Directional inter-chain (polymer) inter-molecular

SUMMARY: PRIMARY BONDS

Ceramics

(Ionic & covalent bonding):

Large bond energy

large T_m
large E
small α

Metals

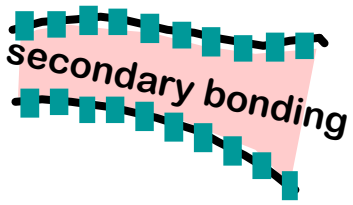
(Metallic bonding):

Variable bond energy

moderate T_m
moderate E
moderate α

Polymers

(Covalent & Secondary):



Directional Properties

Secondary bonding dominates
small T
small E
large α

READING SCHEDULE

Reading Schedule	week	chapter
Introduction	0	-
General Introduction Atomic Bonding	1	1 e 2
Crystalline Structure; Imperfections	**2**	**3 e 4**
Diffusion; Mechanical Properties	3	5 e 6
Strengthening Mechanisms; Failure	4	7 e 8
Phase Diagrams	5	9
Kinetics & Phase Transformations	6	10
Processing & Applications of Metals	7	11
Structure, Properties, Process and Applications of Ceramics	8	12 e 13
Structure, Properties, Process of Polymers and Composites	9	15 e 16
Corrosion; Electrical & Thermal Properties	10	**17, 18 e 19**
Magnetic & Optical Properties	11	20 e 21
Economic & Environmental Issues; Materials Selection	12	22

CALLISTER JR., WILLIAM D., Ciência e Engenharia dos Materiais: Uma Introdução, 1a ed., Rio de Janeiro, LTC, 2002, ISBN: 85-216-2188-5

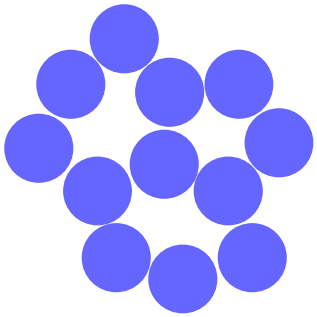
CHAPTER 3: CRYSTAL STRUCTURES & PROPERTIES

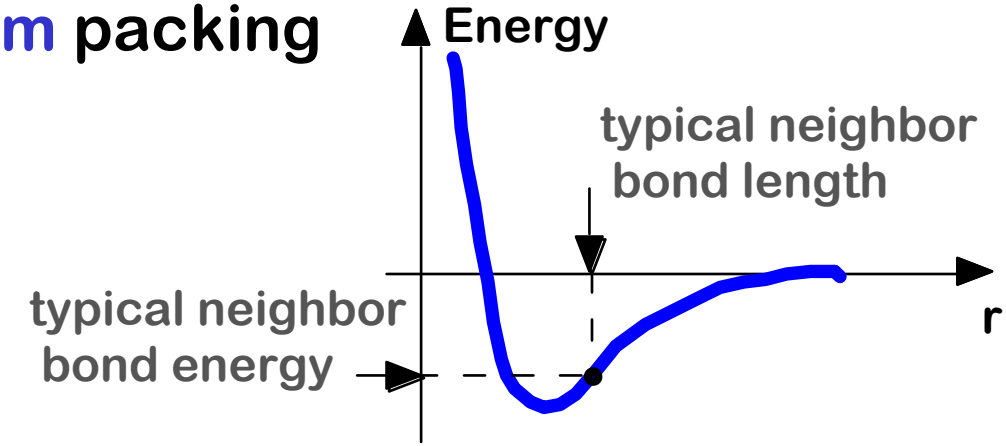
ISSUES TO ADDRESS...

- **How do atoms assemble into solid structures? (for now, focus on metals)**
- **How does the density of a material depend on its structure?**
- **When do material properties vary with the sample (i.e., part) orientation?**

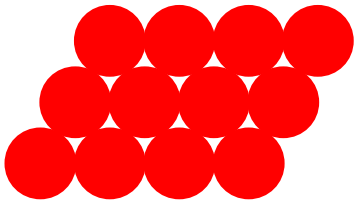
ENERGY AND PACKING

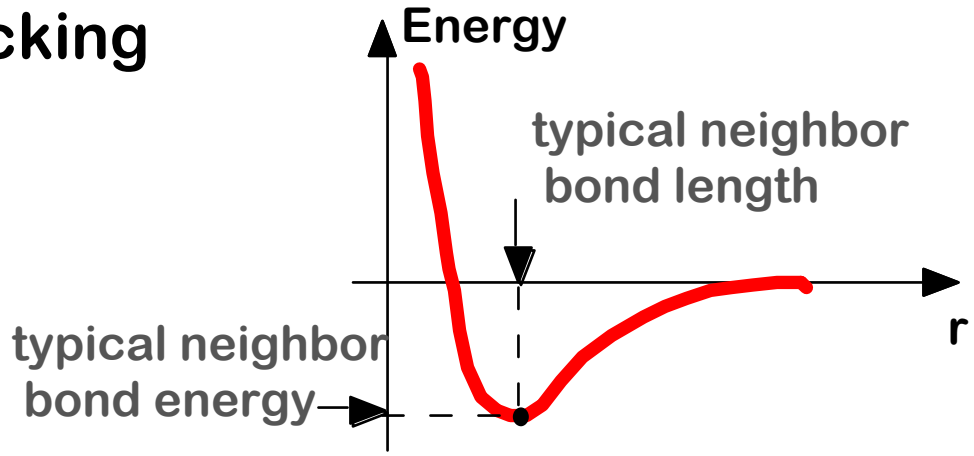
- Non dense, random packing





- Dense, regular packing



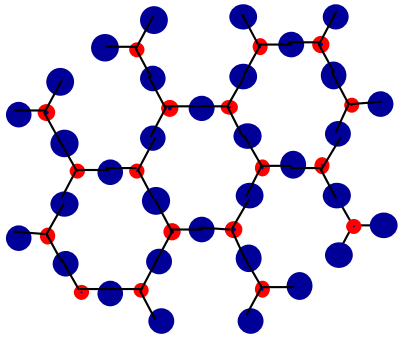


Dense, regular-packed structures tend to have lower energy.

MATERIALS AND PACKING

Crystalline materials...

- atoms pack in periodic, 3D arrays
- typical of: -metals
  -many ceramics
  -some polymers



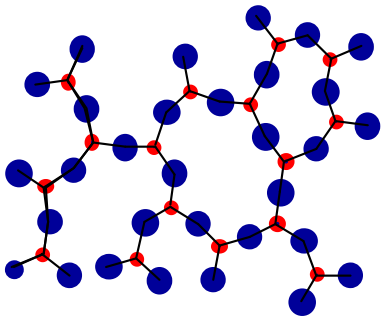
crystalline SiO_2

Adapted from Fig. 3.18(a), *Callister 6e.*

• Si ● Oxygen

Noncrystalline materials...

- atoms have no periodic packing
- occurs for: -complex structures
  -rapid cooling



noncrystalline SiO_2

Adapted from Fig. 3.18(b), *Callister 6e.*

"Amorphous" = Noncrystalline

METALLIC CRYSTALS

- **tend to be densely packed.**
- **have several reasons for dense packing:**

  -Typically, only one element is present, so all atomic radii are the same.

  -Metallic bonding is not directional.

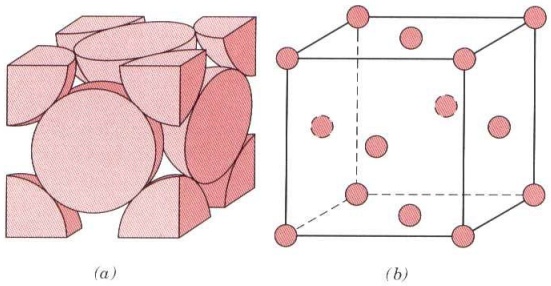
  -Nearest neighbor distances tend to be small in order to lower bond energy.

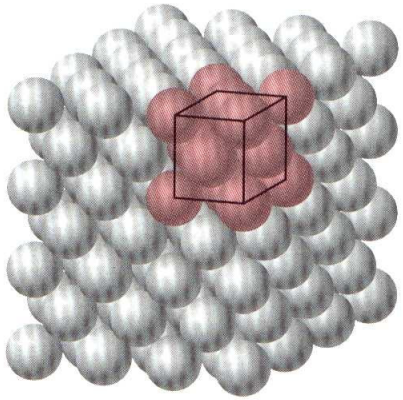
- **have the simplest crystal structures.**

We will look at three such structures...

CÉLULA UNITÁRIA

(unidade básica repetitiva da estrutura tridimensional)



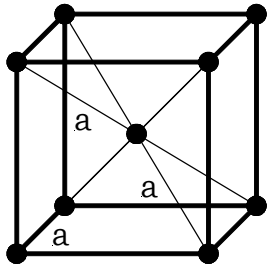


Célula Unitária

Os átomos são representados como esferas rígidas

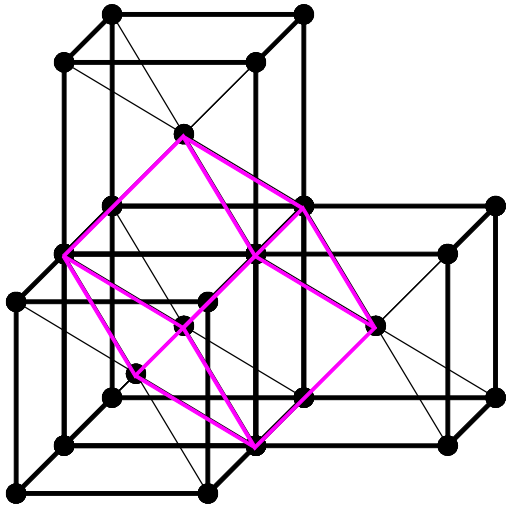
Unit Cell vs. Primitive Cell

A volume of space that when translated through all the vectors in a Bravais lattice just fills all of space without overlapping or leaving voids is called a *primitive cell* of the lattice. A primitive cell contains just one Bravais lattice point (recall that a crystal lattice is formed by placing one or more atoms at each Bravais lattice point). The primitive cell is the smallest cell that can be translated throughout space to completely recreate the entire lattice. There is not one unique shape to a primitive cell and many possible shapes fulfill the definition. The primitive cell for the simple cubic lattice is equal to the simple cubic unit cell (they are identical in shape). A common choice for the primitive cell of the body-centered cubic lattice is shown below.



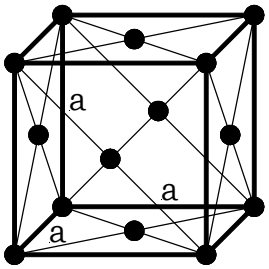
Body-Centered Cubic (I)

Unit Cell



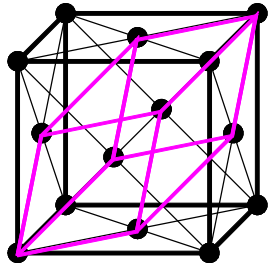
Primitive Cell (magenta)

Unit Cell vs. Primitive Cell

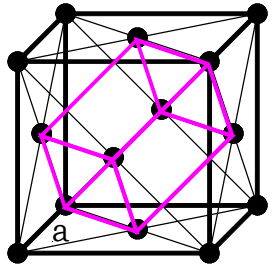


Face-Centered Cubic (F)

Unit Cell



Primitive Cell



Rotated 90°

The primitive cell is smaller or equal in size to the unit cell. The unit cells help to remind us of the symmetry (ie. Cubic).

Bravais Lattice

$$\mathbf{R} = n_1 \mathbf{a}_1 + n_2 \mathbf{a}_2$$

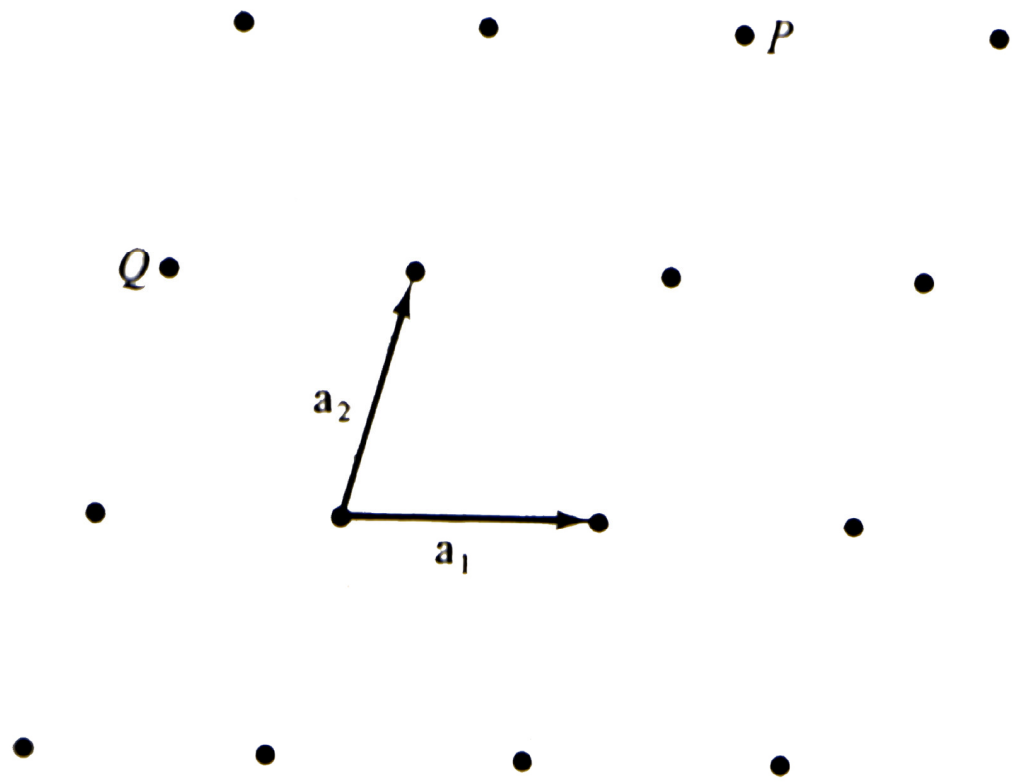


FIGURE A general two-dimensional Bravais lattice of no particular symmetry: the oblique net. Primitive vectors $\mathbf{a}_1$ and $\mathbf{a}_2$ are shown. All points in the net are linear combinations of these with integral coefficients; for example, $P = \mathbf{a}_1 + \mathbf{a}_2$, and $Q = -\mathbf{a}_1 + \mathbf{a}_2$. (Ashcroft, Neil W. *Solid state physics*.)

$$\mathbf{R} = n_1 \mathbf{a}_1 + n_2 \mathbf{a}_2 + n_3 \mathbf{a}_3$$

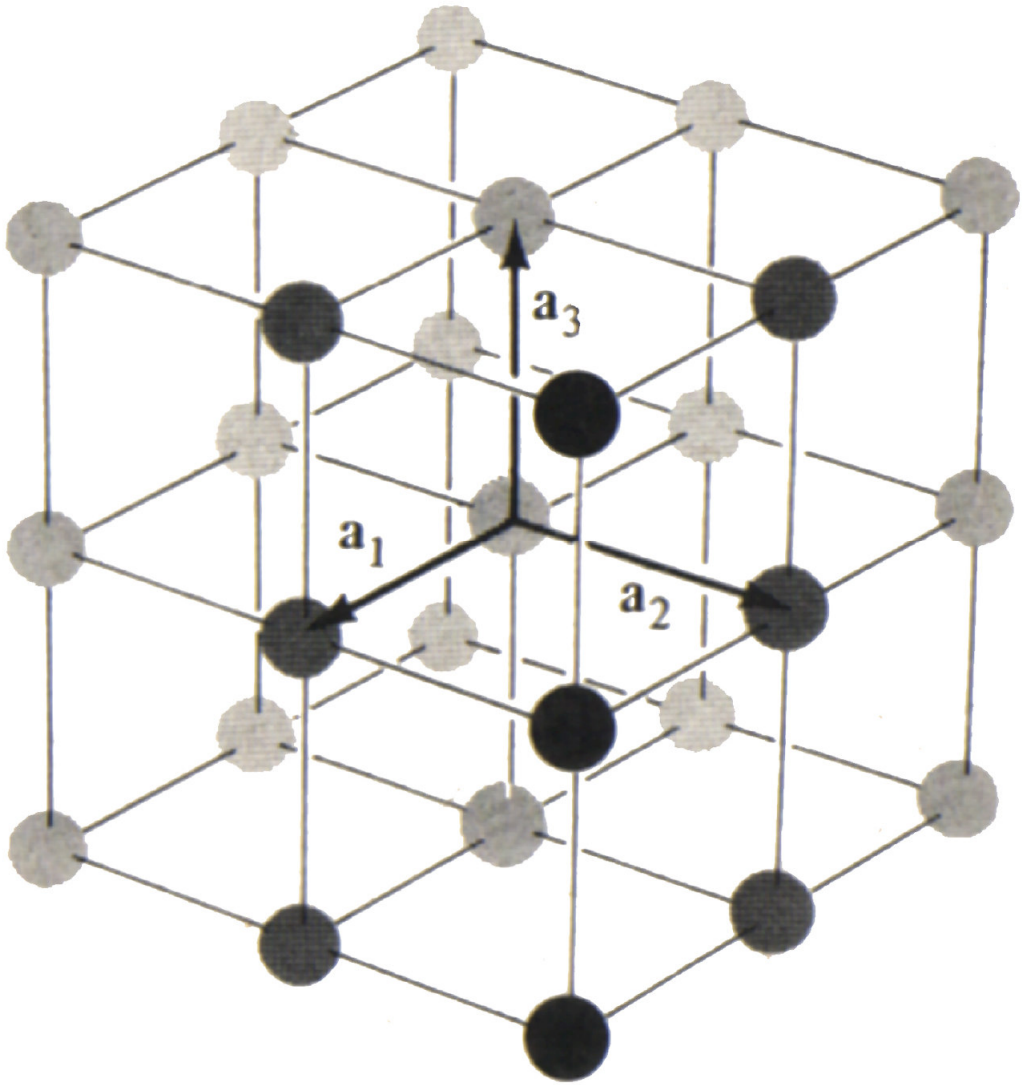


FIGURE A simple cubic three-dimensional Bravais lattice. The three primitive vectors can be taken to be mutually perpendicular, and with a common magnitude. (Ashcroft, Neil W. *Solid state physics*.)

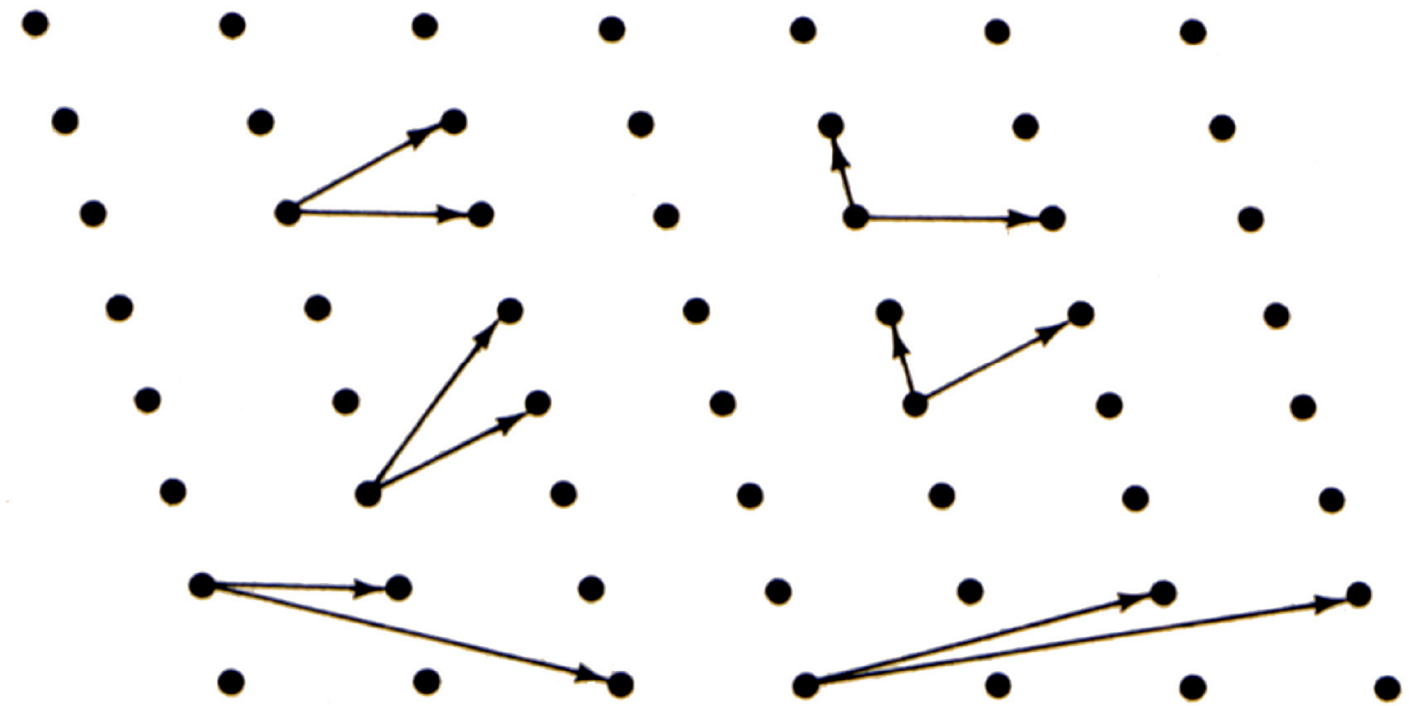


FIGURE Several possible choices of pairs of primitive vectors for a two-dimensional Bravais lattice. They are drawn, for clarity, from different origins. (Ashcroft, Neil W. *Solid state physics*.)

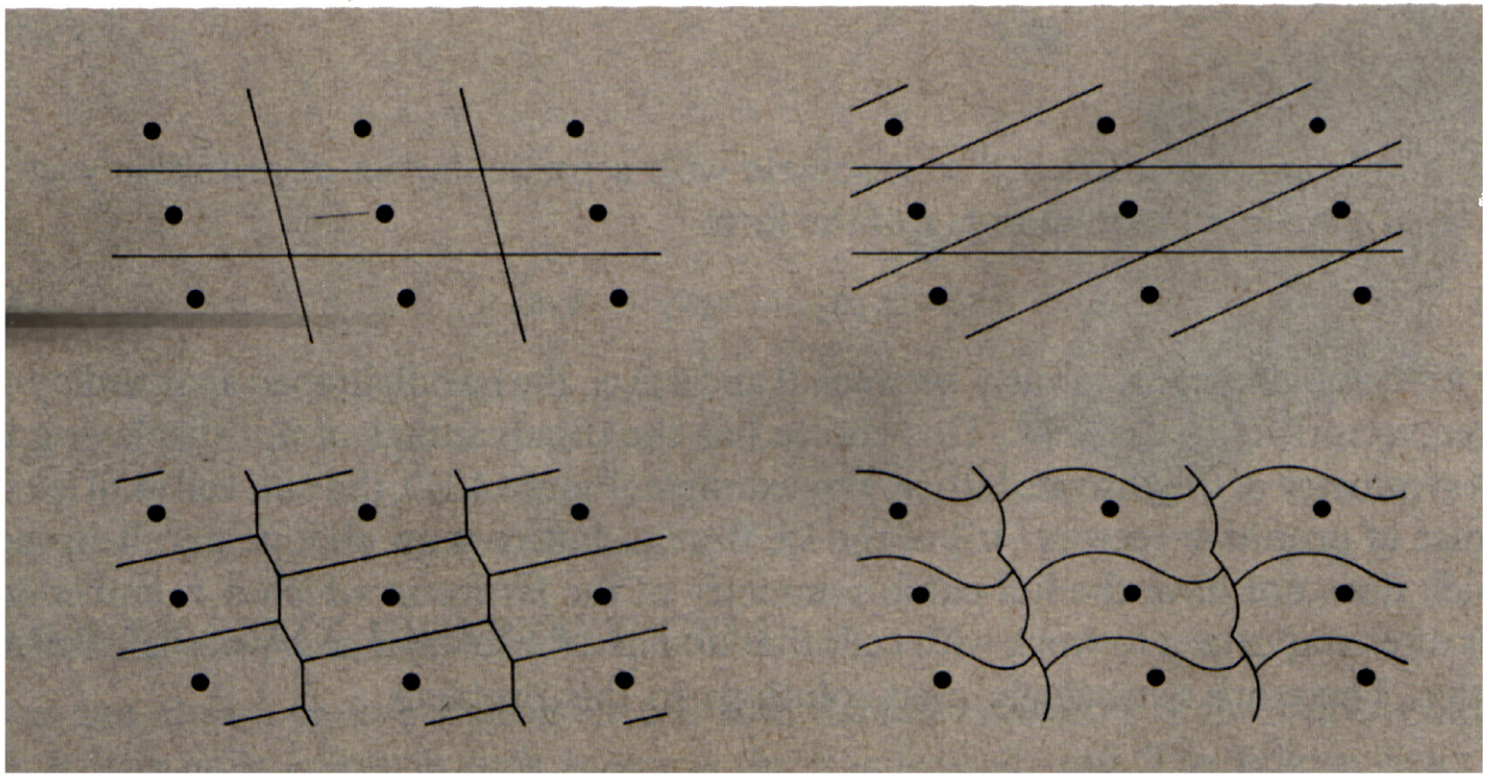
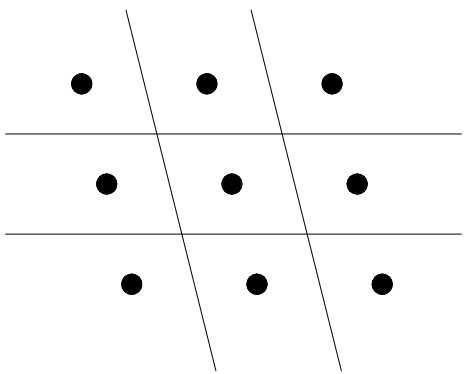
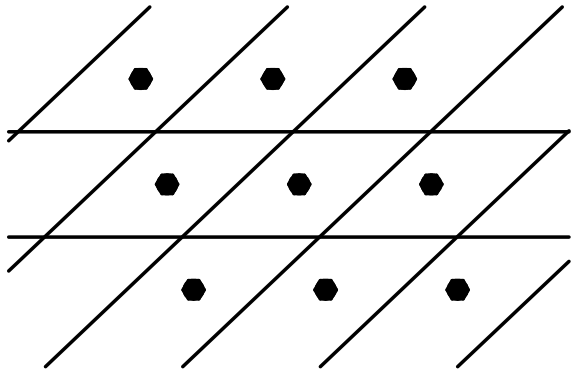


FIGURE Several possible choices of primitive cell for a single two-dimensional Bravais lattice. (Ashcroft, Neil W. *Solid state physics*.)

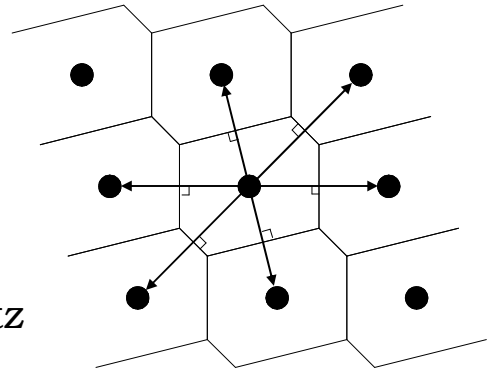
CÉLULA PRIMITIVA

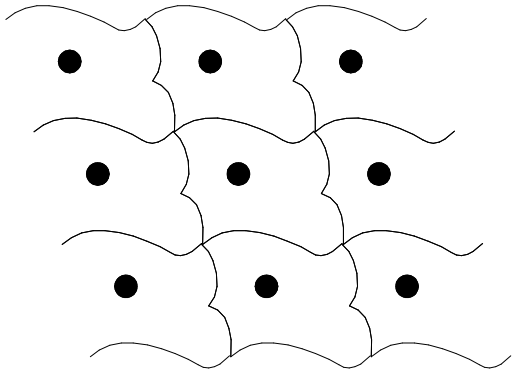
Two Dimensional Lattice





Wigner-Seitz

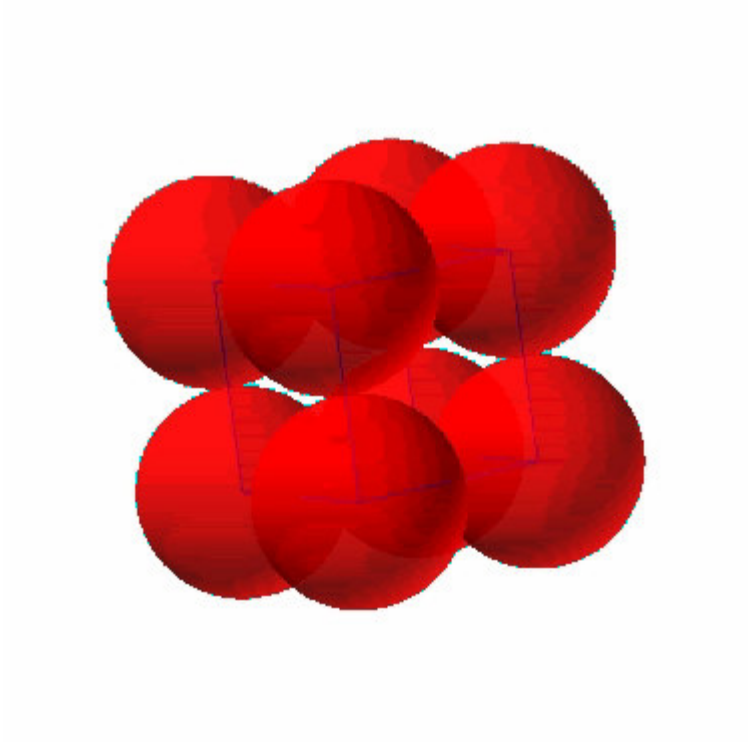




Possible choices of primitive cell for a single 2D Bravais lattice.

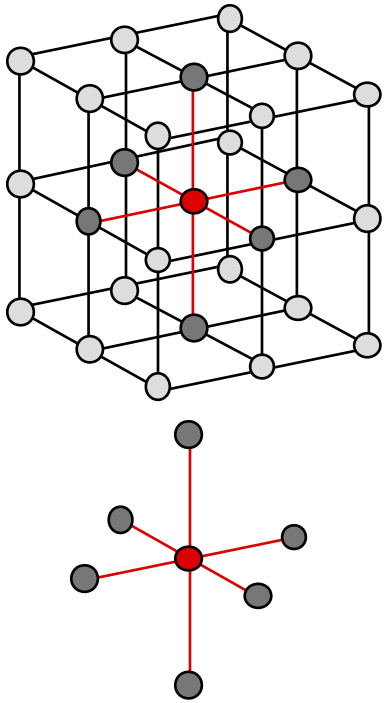
SIMPLE CUBIC STRUCTURE (SC)

- **Rare due to poor packing (only Po has this structure)**
- **Close-packed directions are cube edges.**



(Courtesy P.M. Anderson)

- **Coordination # = 6**
  (# nearest neighbors)

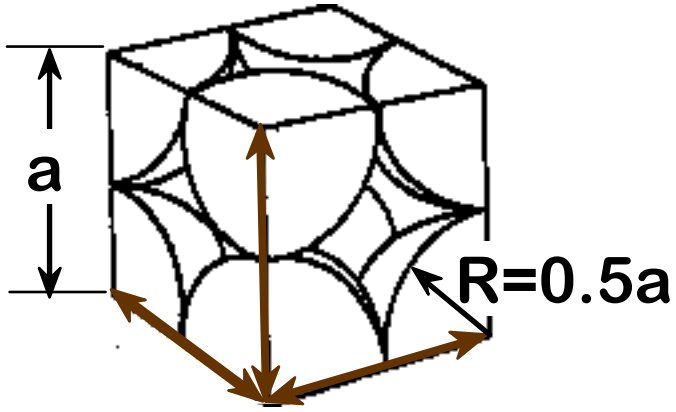


ATOMIC PACKING FACTOR

$$APF = \frac{\text{Volume of atoms in unit cell}^*}{\text{Volume of unit cell}}$$

*assume hard spheres

- APF for a simple cubic structure = 0.52



close-packed directions

contains 8 x 1/8 =

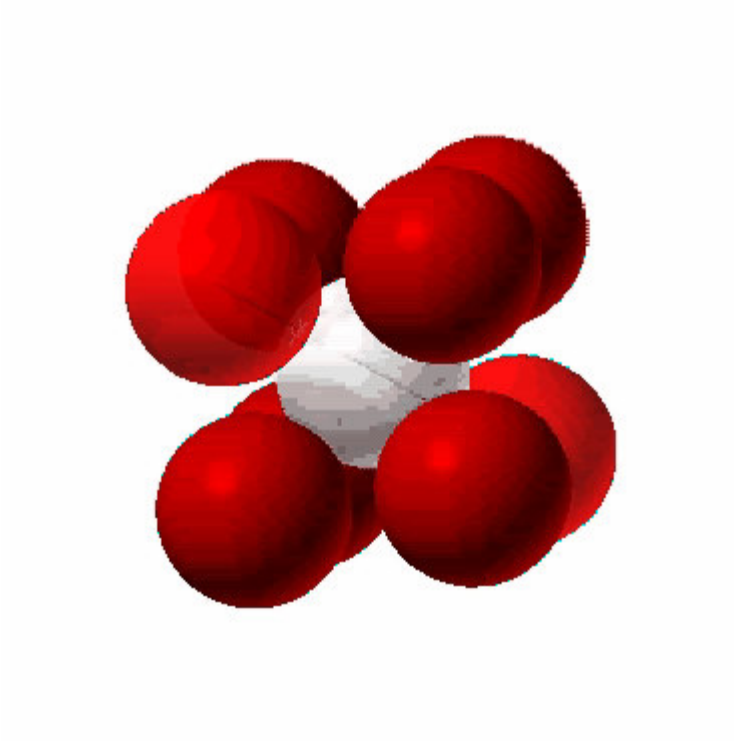
1 atom/unit cell

$$APF = \frac{\frac{\text{atoms}}{\text{unit cell}} \cdot \frac{\text{volume}}{\text{atom}}}{\frac{\text{volume}}{\text{unit cell}}} = \frac{1 \cdot \frac{4}{3}\pi (0.5a)^3}{a^3}$$

Adapted from Fig. 3.19, *Callister 6e.*

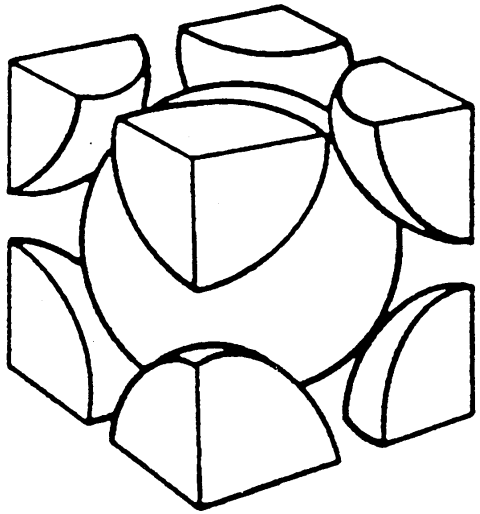
BODY CENTERED CUBIC STRUCTURE (BCC)

- **Close packed directions are cube diagonals.**
  --Note: All atoms are identical; the center atom is shaded differently only for ease of viewing.

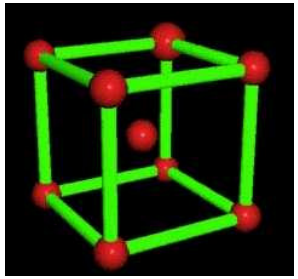


(Courtesy P.M. Anderson)

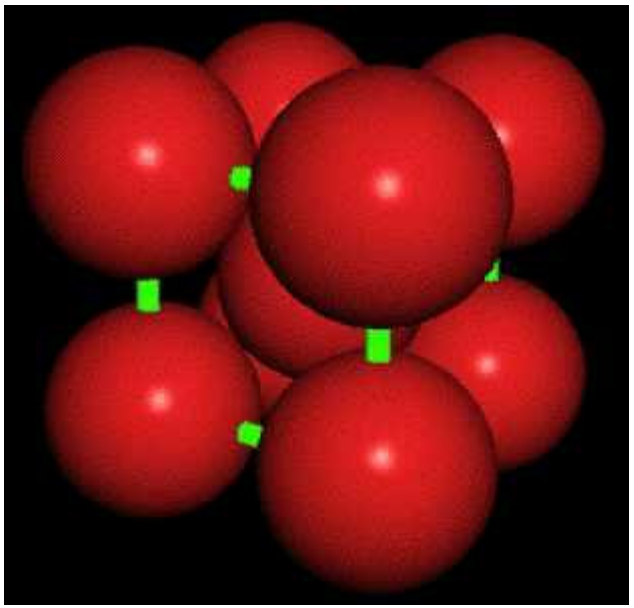
- **Coordination # = 8**



Adapted from Fig. 3.2, *Callister 6e.*



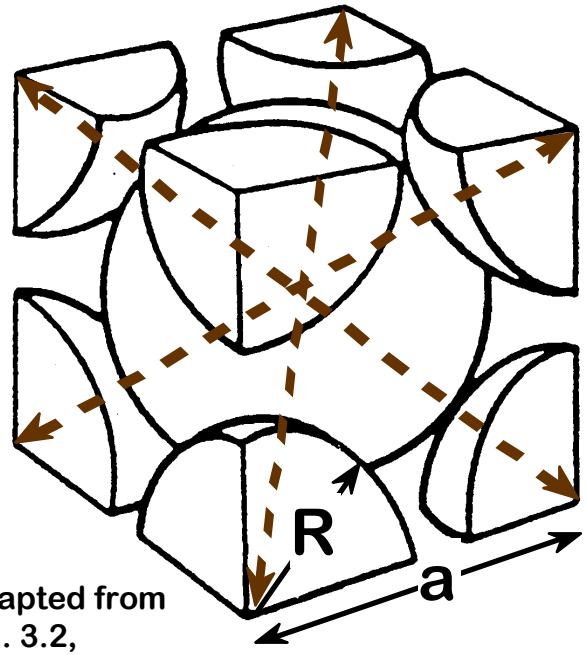
EST. CÚBICA DE CORPO CENTRADO



- Na est. ccc cada átomo dos vertices do cubo é dividido com 8 células unitárias
- Já o átomo do centro pertence somente a sua célula unitária.
- Cada átomo de uma estrutura ccc é cercado por 8 átomos adjacentes
- Há 2 átomos por célula unitária na estrutura ccc
- O Fe, Cr, W cristalizam em ccc

ATOMIC PACKING FACTOR: BCC

- APF for a body-centered cubic structure = 0.68



Adapted from Fig. 3.2, *Callister 6e.*

Close-packed directions:

length = 4R

$= \sqrt{3}\, a$

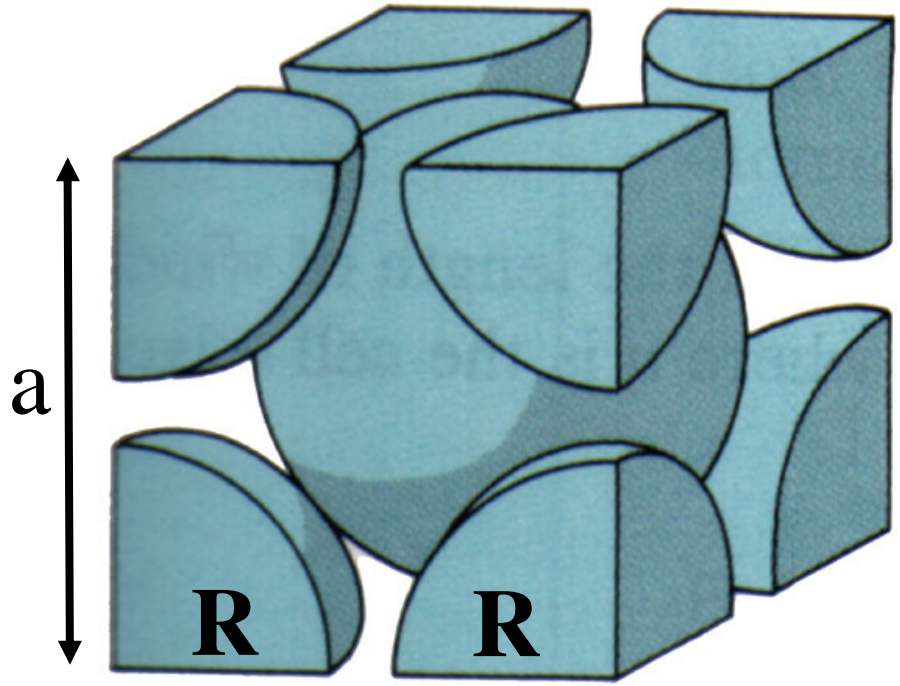
Unit cell contains:

1 + 8 x 1/8

= 2 atoms/unit cell

$$APF = \frac{\left(\frac{\text{atoms}}{\text{unit cell}}\right)\left(\frac{\text{volume}}{\text{atom}}\right)}{\frac{\text{volume}}{\text{unit cell}}} = \frac{2\left(\frac{4}{3}\pi\left(\sqrt{3}a/4\right)^3\right)}{a^3}$$

- Calcule a densidade linear de uma BCC na direcao [100]
- $a=4R/\sqrt{3}$
- $LD=L_C/L_l=2R/(4R/\sqrt{3})=0.866$



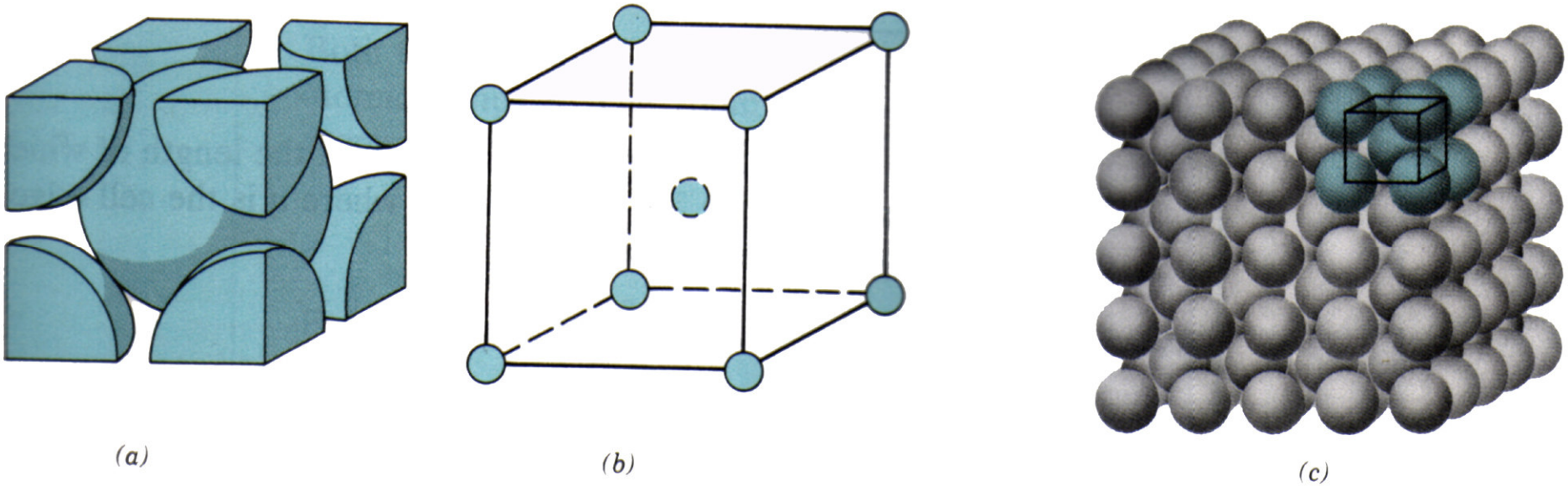


FIGURE 3.2 For the body-centered cubic crystal structure, (a) a hard sphere unit cell representation, (b) a reduced-sphere unit cell, and (c) an aggregate of many atoms. (William D. Callister, JR. *Materials Science and Engineering an Introduction*, John Wiley & Sons, Inc.)

Body-centered cubic Bravais lattice

Primitive vectors

$$\mathbf{a}_1 = a\hat{\mathbf{x}}, \quad \mathbf{a}_2 = a\hat{\mathbf{y}}, \quad \mathbf{a}_3 = \frac{a}{2}\left(\hat{\mathbf{x}} + \hat{\mathbf{y}} + \hat{\mathbf{z}}\right) \qquad (4.3)$$

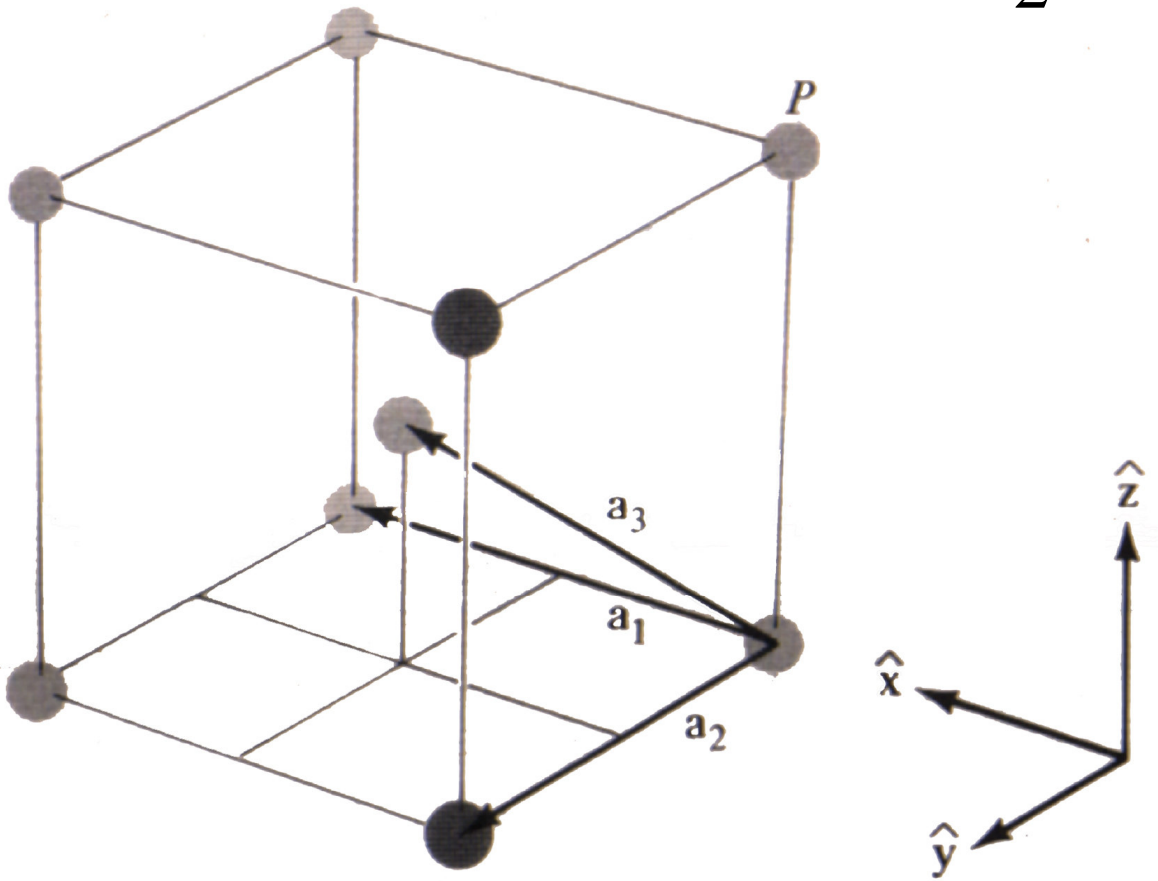


FIGURE Three primitive vectors, specified in Eq. (4.3), for the body-centered cubic Bravais lattice. The lattice is formed by taking all linear combinations of the primitive vectors with integral coefficients. The point P, for example, is $\mathbf{P} = -\mathbf{a}_1 - \mathbf{a}_2 + 2\mathbf{a}_3$. (Ashcroft, Neil W. *Solid state physics*.)

Body-centered cubic Bravais lattice

Primitive vectors

$$\mathbf{a}_1 = \frac{a}{2}(-\hat{x}+\hat{y}+\hat{z}),\quad \mathbf{a}_2 = \frac{a}{2}(\hat{x}-\hat{y}+\hat{z}),\quad \mathbf{a}_3 = \frac{a}{2}(\hat{x}+\hat{y}-\hat{z}) \qquad (4.4)$$

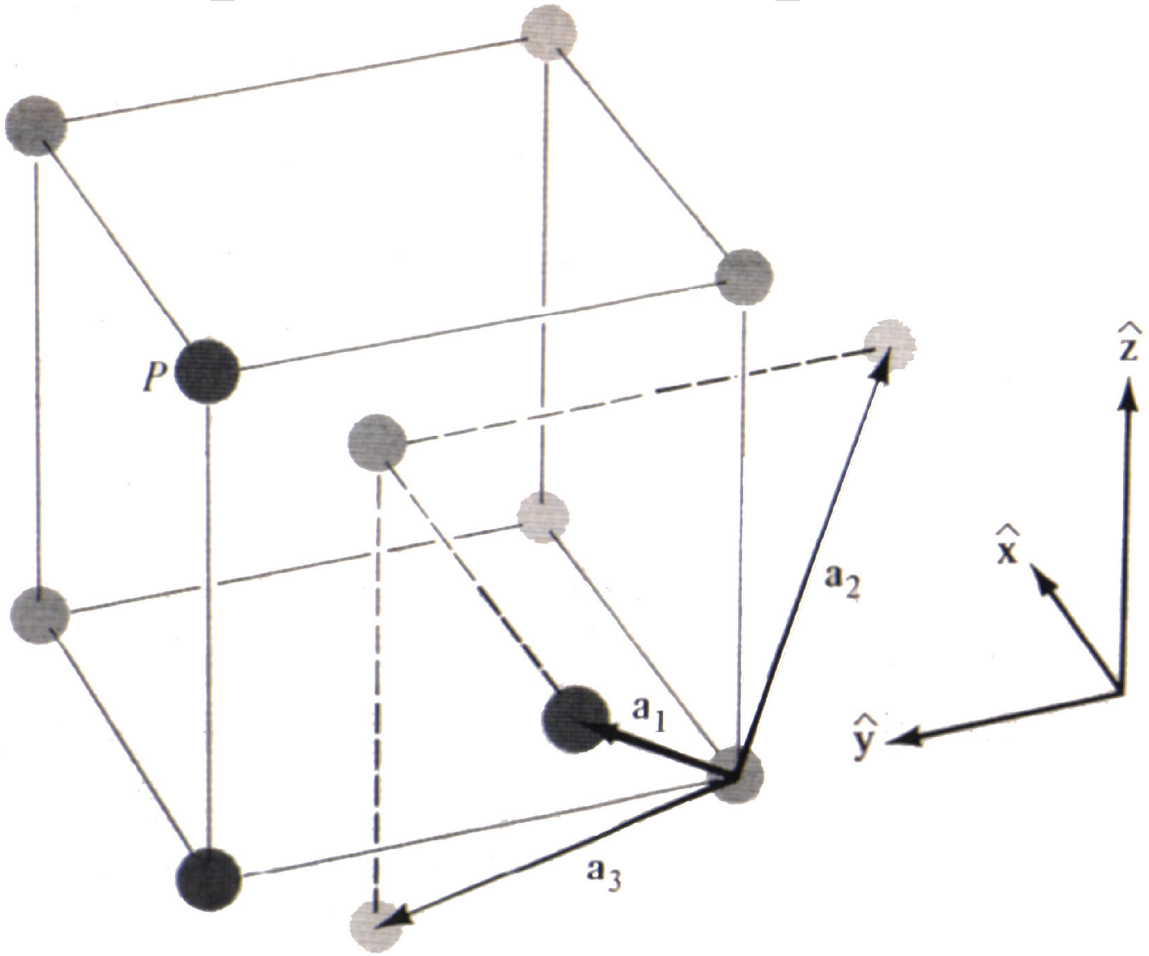
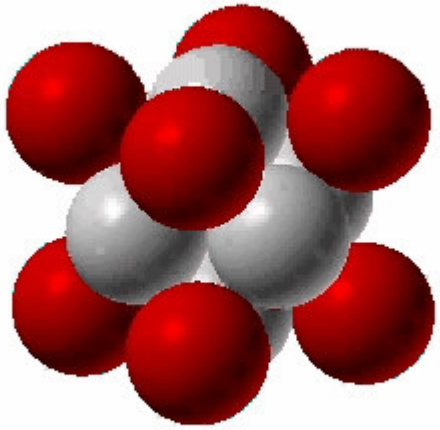


FIGURE A more symmetric set of primitive vectors, specified in Eq. (4.4), for the body-centered cubic Bravais lattice. The point P, for example, has the form P = 2 $\mathbf{a}_1$ + $\mathbf{a}_2$ + $\mathbf{a}_3$. (Ashcroft, Neil W. *Solid state physics*.)

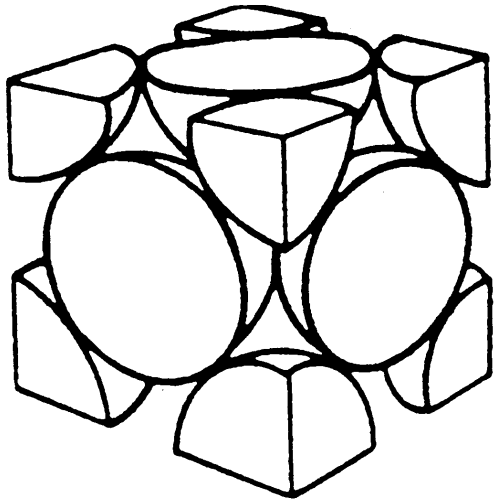
FACE CENTERED CUBIC STRUCTURE (FCC)

- **Close packed directions are face diagonals.**
  --Note: All atoms are identical; the face-centered atoms are shaded differently only for ease of viewing.

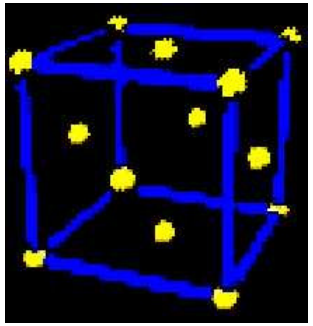
- **Coordination # = 12**



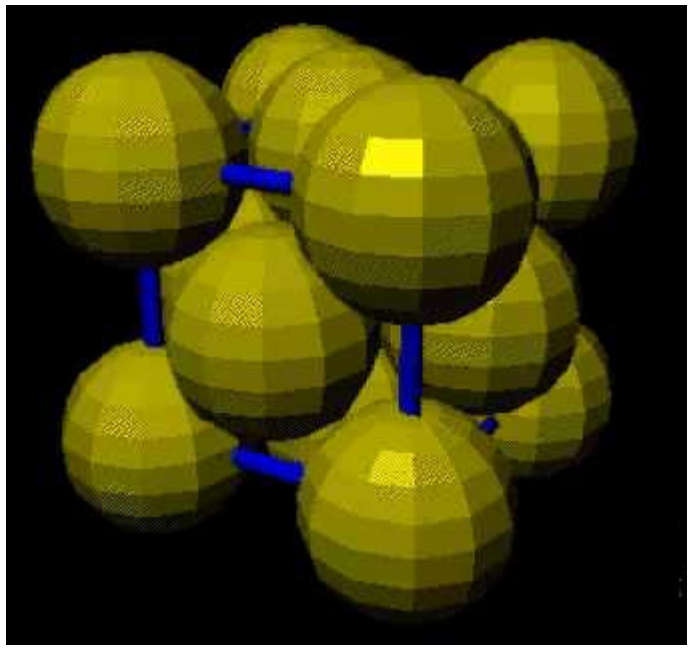
(Courtesy P.M. Anderson)



Adapted from Fig. 3.1(a), *Callister 6e.*

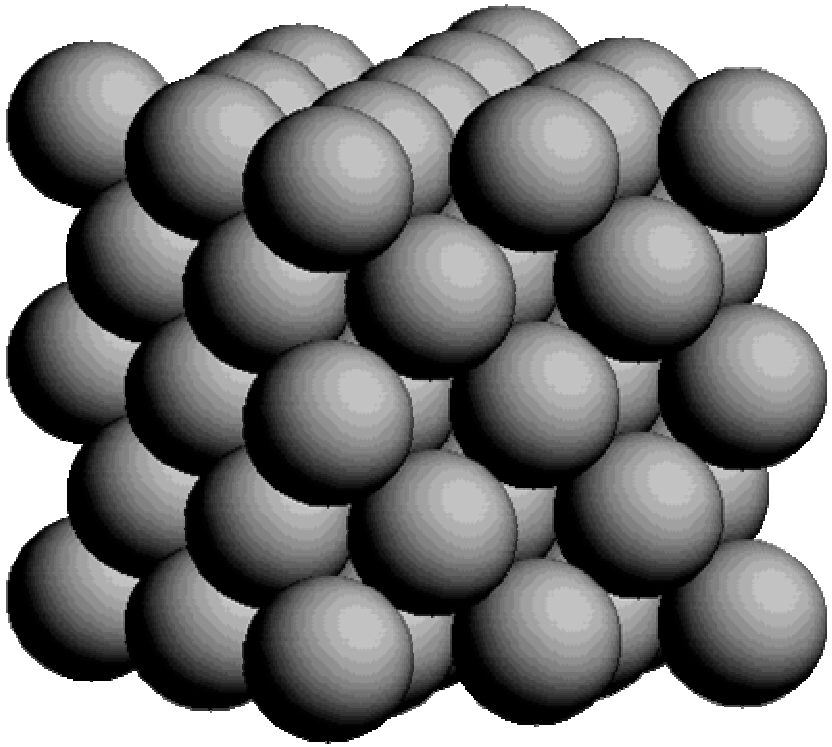


EST. CÚBICA DE FACE CENTRADA



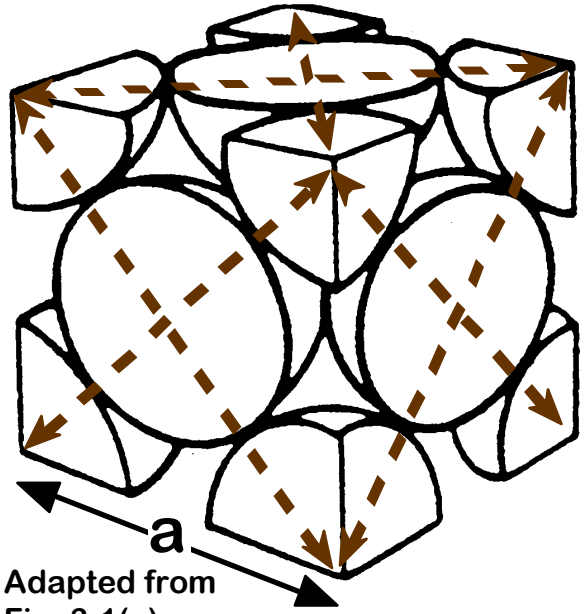
- Na est. cfc cada átomo dos vertices do cubo é dividido com 8 células unitátias
- Já os átomos das faces pertencem somente a duas células unitárias
- Há 4 átomos por célula unitária na estrutura cfc
- É o sistema mais comum encontrado nos metais (Al, Fe, Cu, Pb, Ag, Ni,...)

Face Centered Cubic Lattice (111)
Hard Sphere Model



ATOMIC PACKING FACTOR: FCC

- APF for a body-centered cubic structure = 0.74



Adapted from Fig. 3.1(a), *Callister 6e.*

Close-packed directions:

length = 4R

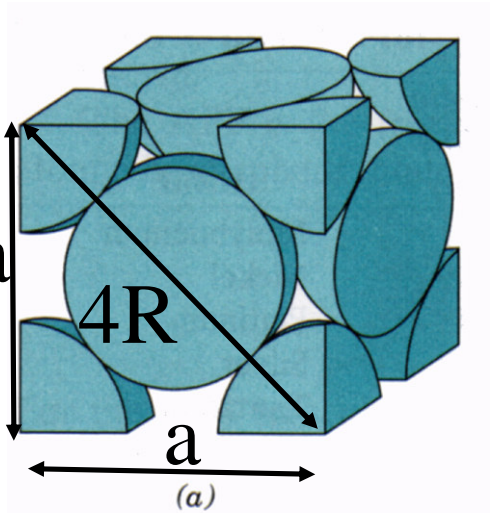
$= \sqrt{2}\,a$

Unit cell contains:

6 x 1/2 + 8 x 1/8

= 4 atoms/unit cell

$$APF = \frac{\text{atoms}}{\text{unit cell}} \cdot \frac{\text{volume}}{\text{atom}} \Big/ \frac{\text{volume}}{\text{unit cell}} = \frac{4 \cdot \frac{4}{3}\pi\left(\sqrt{2}a/4\right)^3}{a^3}$$



$$APF = \frac{Volume\ Total\ da\ Esfera\ (V_S)}{Volume\ Total\ da\ Celula\ Unitaria\ (V_C)}$$

$$V_S = 4\frac{4}{3}\pi R^3$$

$$V_C = 16R^3\sqrt{2}$$

$$APF = 0.74$$

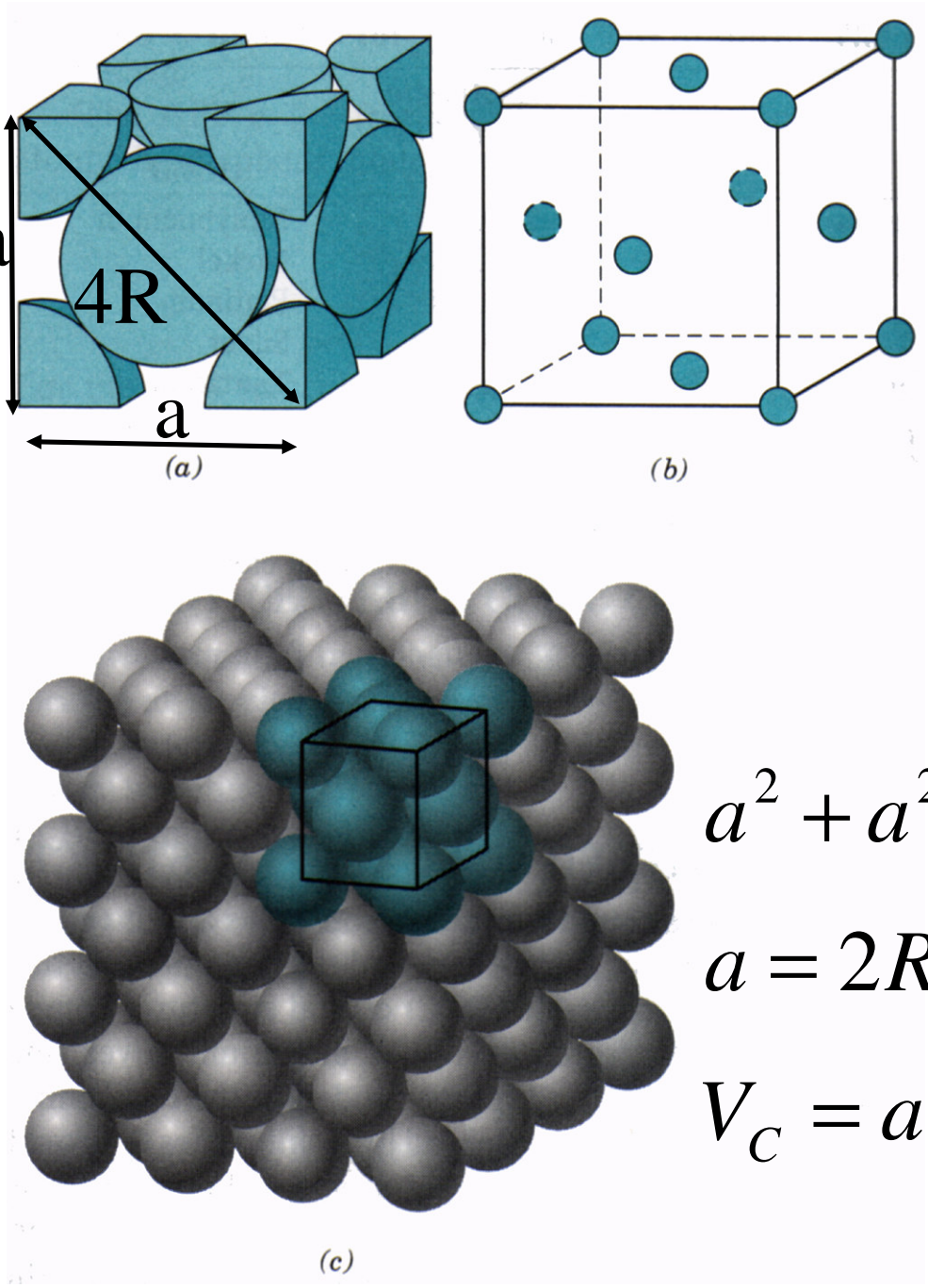


FIGURE 3.1 For the face-centered cubic crystal structure: (a) a hard sphere unit cell representation, (b) a reduced-sphere unit cell, and (c) an aggregate of many atoms. (William D. Callister, JR. *Materials Science and Engineering an Introduction*, John Wiley & Sons, Inc.)

$$a^2 + a^2 = (4R)^2$$

$$a = 2R\sqrt{2}$$

$$V_C = a^3 = (2R\sqrt{2})^3 = 16R^3\sqrt{2}$$

Face-centered cubic Bravais lattice

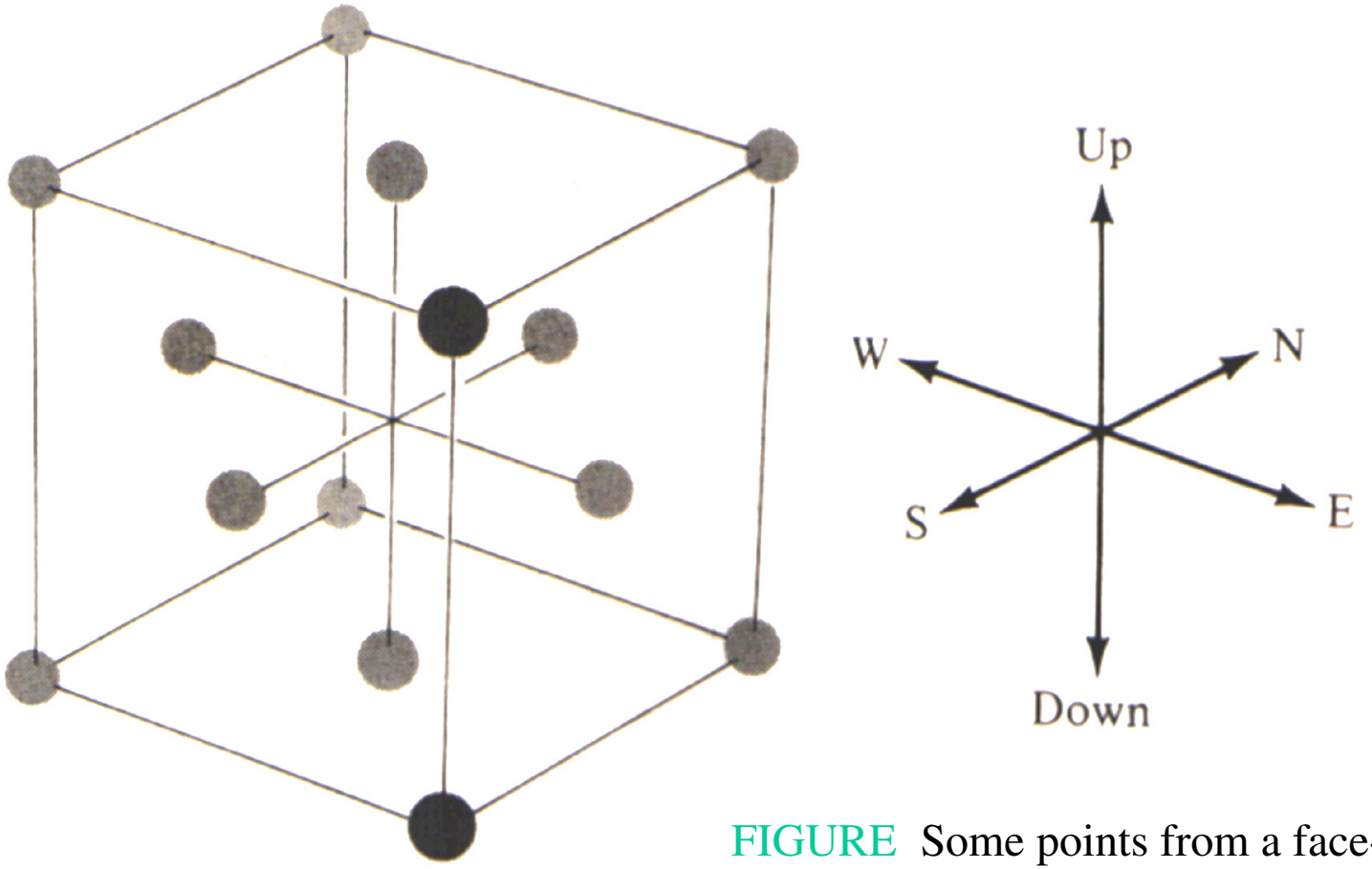


FIGURE Some points from a face-centered cubic Bravais lattice. (Ashcroft, Neil W. *Solid state physics*.)

Face-centered cubic Bravais lattice

Primitive vectors

$$\mathbf{a}_1 = \frac{a}{2}(\hat{y} + \hat{z}), \quad \mathbf{a}_2 = \frac{a}{2}(\hat{x} + \hat{z}), \quad \mathbf{a}_3 = \frac{a}{2}(\hat{x} + \hat{y}). \qquad (4.5)$$

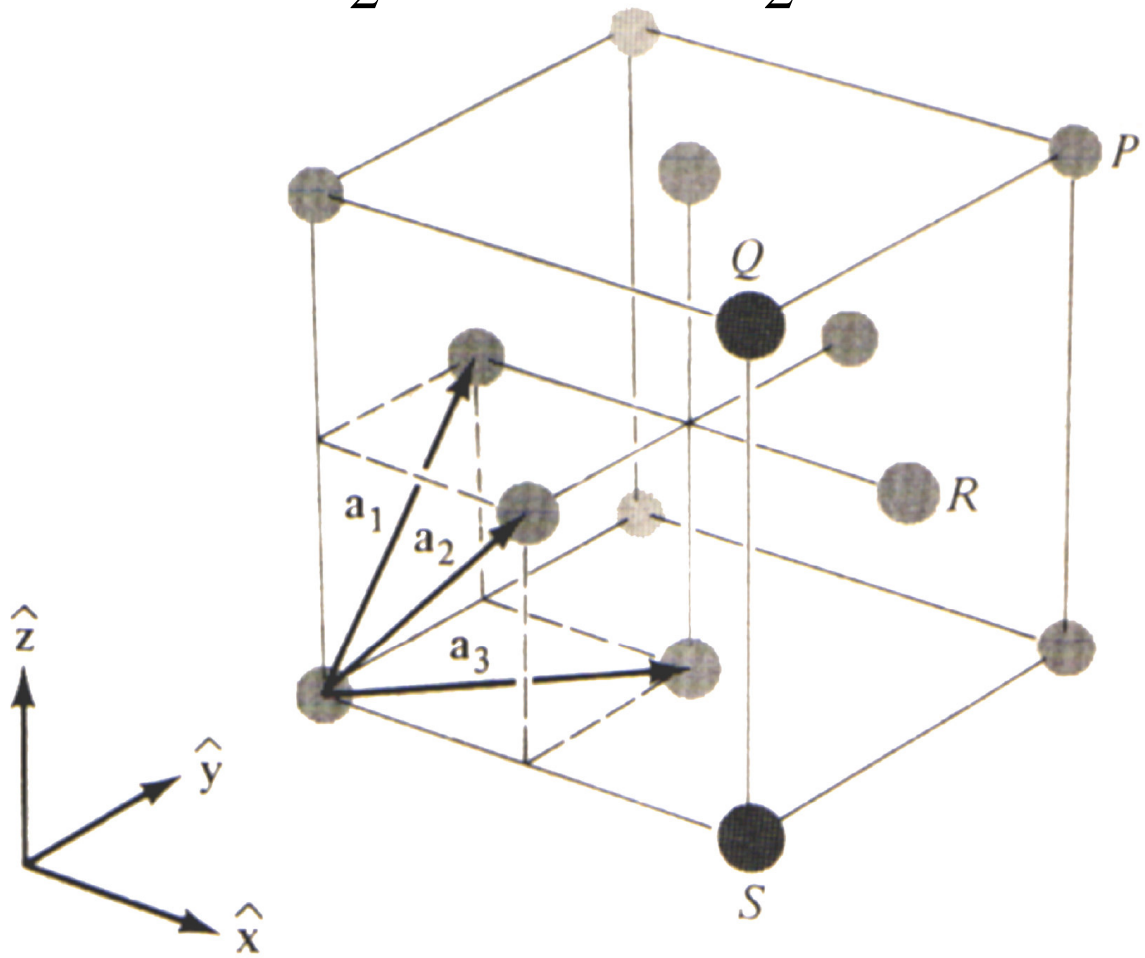
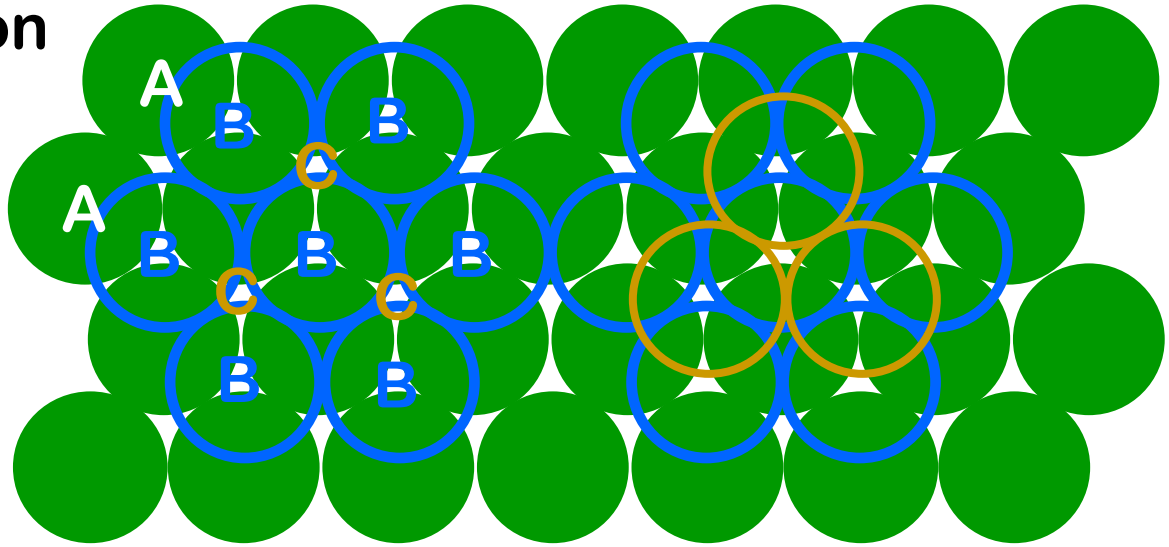


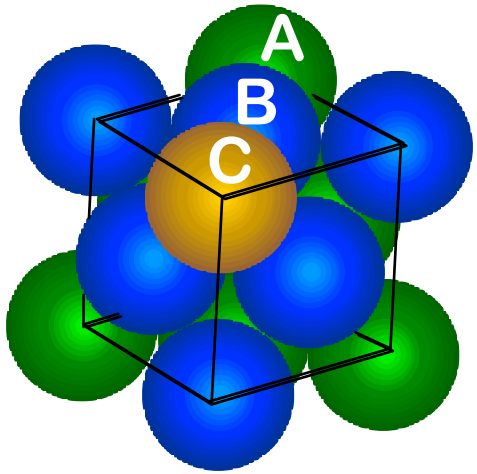
FIGURE A set of primitive vectors, as given in Eq. (4.5), for the face-centered cubic Bravais lattice. The labeled points are $\mathbf{P} = \mathbf{a}_1 + \mathbf{a}_2 + \mathbf{a}_3$, $\mathbf{Q} = 2\mathbf{a}_2$, $\mathbf{R} = \mathbf{a}_2 + \mathbf{a}_3$, and $\mathbf{S} = -\mathbf{a}_1 + \mathbf{a}_2 + \mathbf{a}_3$. (Ashcroft, Neil W. *Solid state physics*.)

FCC STACKING SEQUENCE

- **ABCABC… Stacking Sequence**
- **2D Projection**

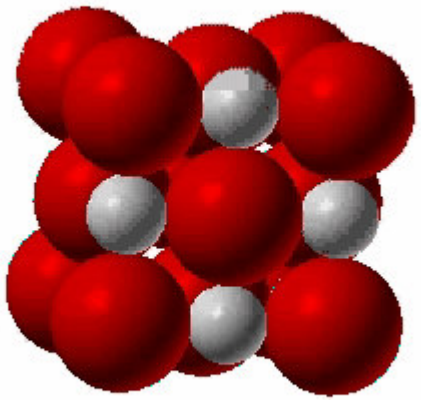


- **FCC Unit Cell**

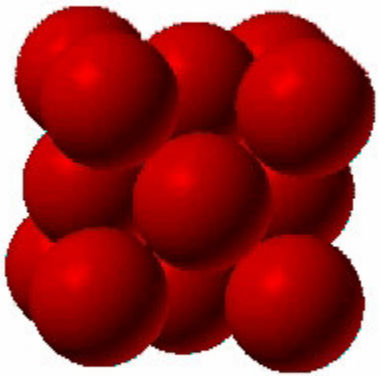


STRUCTURE OF COMPOUNDS: NaCl

- **Compounds: Often have similar close-packed structures.**
- **Structure of NaCl**
- **Close-packed directions**
  --along cube edges.



(Courtesy P.M. Anderson)



(Courtesy P.M. Anderson)

ELEMENTS WITH THE MONATOMIC FACE-CENTERED CUBIC CRYSTAL STRUCTURE

ELEMENT	a (Å)	ELEMENT	a (Å)	ELEMENT	a (Å)
Ar	5.26 (4.2 K)	Ir	3.84	Pt	3.92
Ag	4.09	Kr	5.72 (58 K)	δ-Pu	4.64
Al	4.05	La	5.30	Rh	3.80
Au	4.08	Ne	4.43 (4.2 K)	Sc	4.54
Ca	5.58	Ni	3.52	Sr	6.08
Ce	5.16	Pb	4.95	Th	5.08
β-Co	3.55	Pd	3.89	Xe (58 K)	6.20
Cu	3.61	Pr	5.16	Yb	5.49

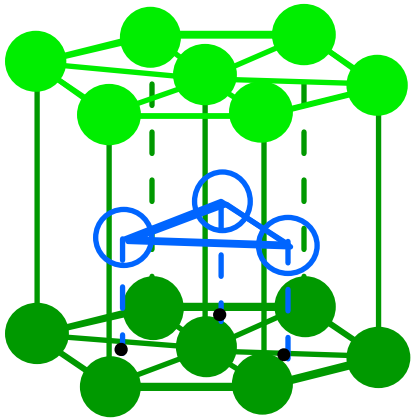
ELEMENTS WITH THE MONATOMIC BODY-CENTERED CUBIC CRYSTAL STRUCTURE

ELEMENT	a (Å)	ELEMENT	a (Å)	ELEMENT	a (Å)
Ba	5.02	Li	3.49 (78 K)	Ta	3.31
Cr	2.88	Mo	3.15	Tl	3.88
Cs	6.05 (78 K)	Na	4.23 (5 K)	V	3.02
Fe	2.87	Nb	3.30	W	3.16
K	5.23 (5 K)	Rb	5.59 (5 K)		

- Materiais metálicos não cristalizam com a estrutura hexagonal simples!
- Eles preferem a hexagonal compacta (HCP). Nessa estrutura o cristal fica no estado de mais baixa energia.
- Fator de empacotamento da FCC = 0,74

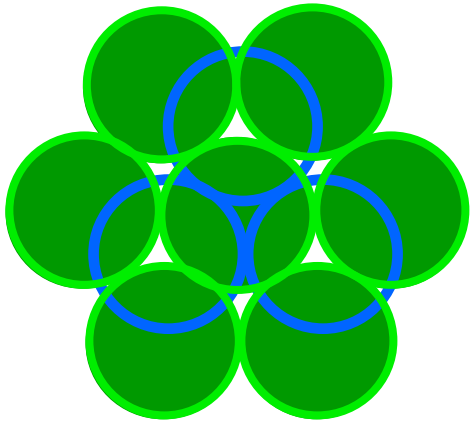
HEXAGONAL CLOSE-PACKED STRUCTURE (HCP)

- ABAB... Stacking Sequence
- 3D Projection



Adapted from Fig. 3.3, *Callister 6e.*

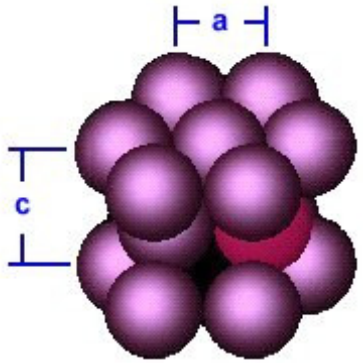
- 2D Projection



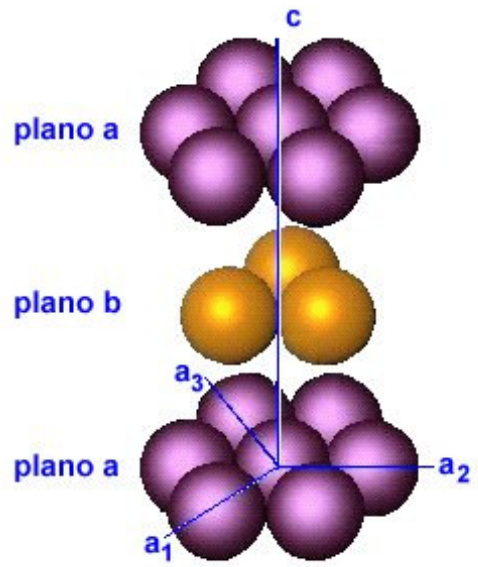
- Coordination # = 12
- APF = 0.74

EST. HEXAGONAL COMPACTA

- Cada átomo tangencia 3 átomos da camada de cima, 6 átomos no seu próprio plano e 3 na camada de baixo do seu plano
- O número de coordenação para a estrutura HC é 12 e, portanto, o fator de empacotamento é o mesmo da cfc, ou seja, 0,74.

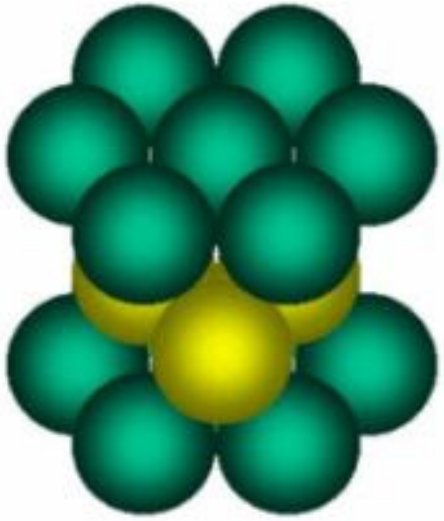


c / a = 1,633

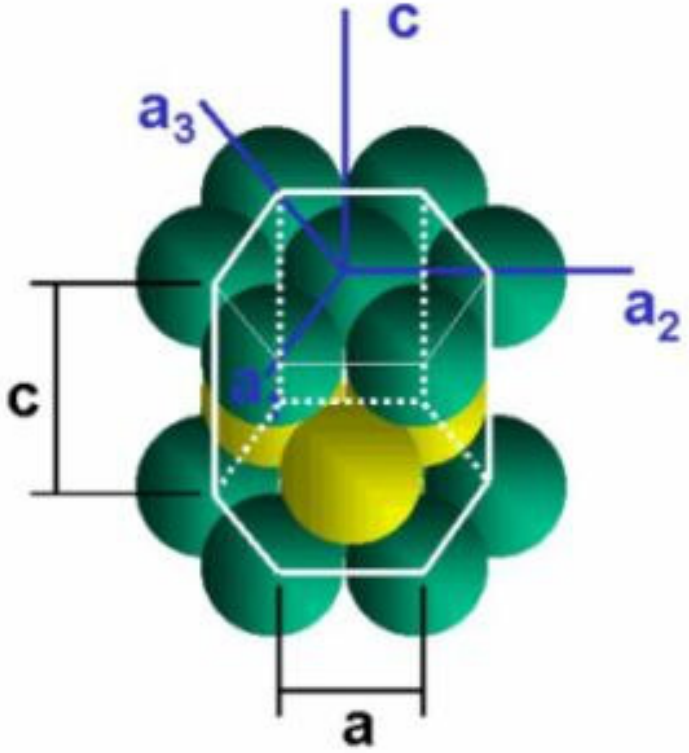


Relação entre R e a:
a= 2R

EST. HEXAGONAL COMPACTA



c / a = 1,633



Há 2 parâmetros de rede representando os parâmetros Basais (a) e de altura (c)

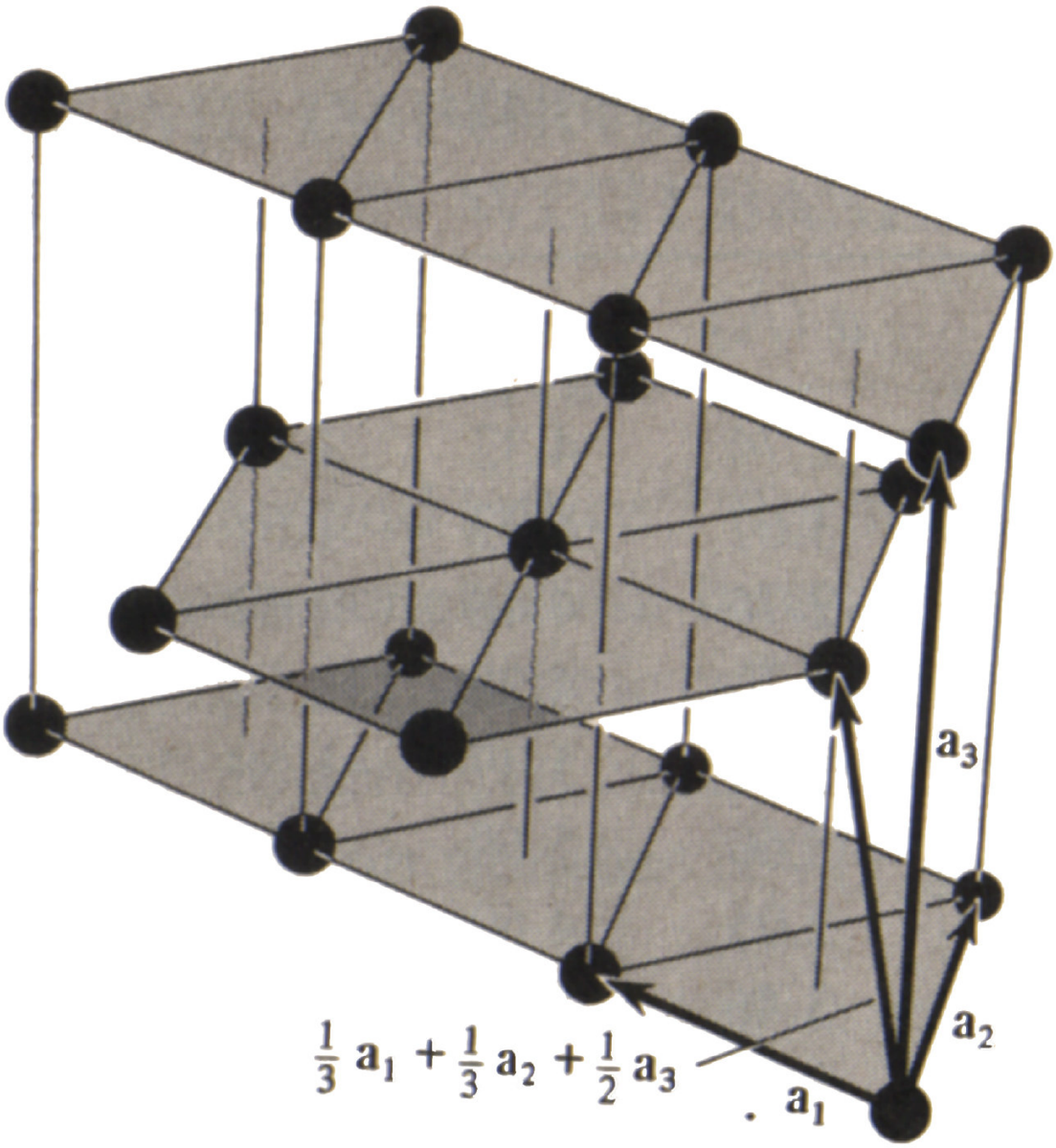


FIGURE The hexagonal close-packed crystal structure. It can be viewed as two interpenetrating simple hexagonal Bravais lattices, displaced vertically by a distance c/2 along the common c-axis, and displaced horizontally so that the points of one lie directly above the centers of the triangles formed by the points of the others. (Ashcroft, Neil W. *Solid state physics*.)

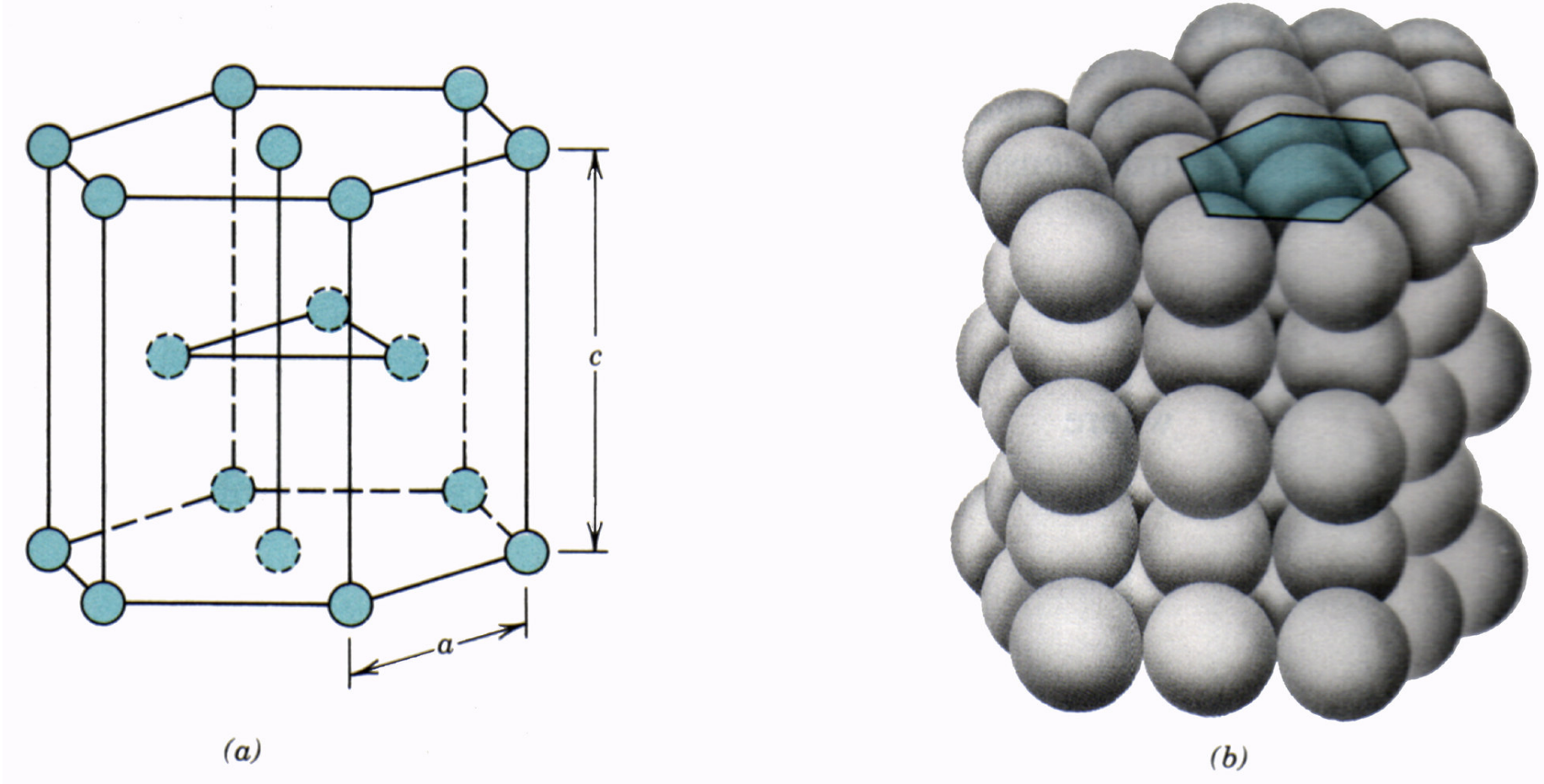


FIGURE 3.3 For the hexagonal close-packed crystal structure, (a) a reduced-sphere unit cell (a and c represent the short and long edge lengths, respectively) and (b) an aggregate of many atoms. (William D. Callister, JR. *Materials Science and Engineering an Introduction*, John Wiley & Sons, Inc.)

OS 7 SISTEMAS CRISTALINOS

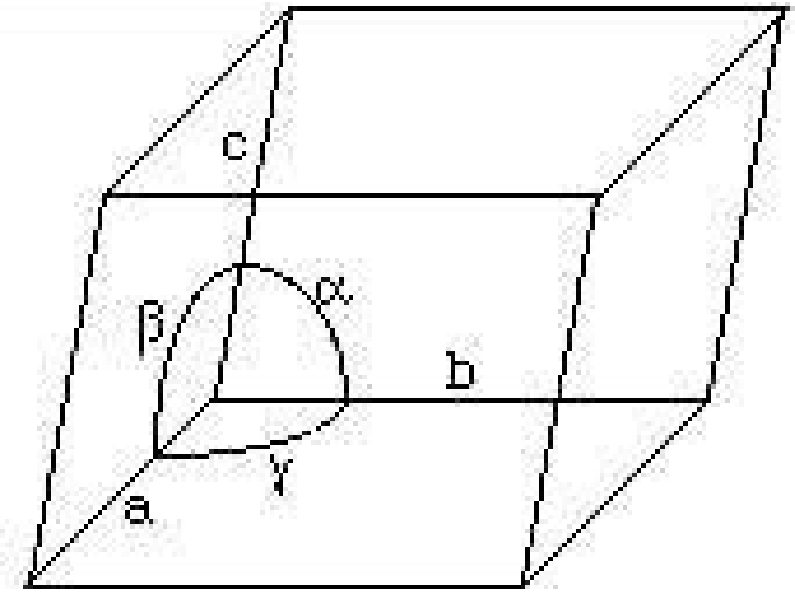
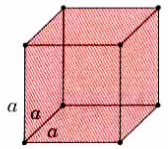
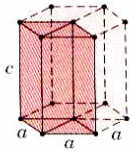
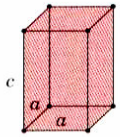
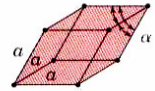
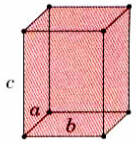
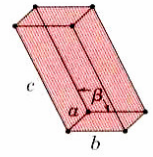
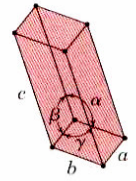
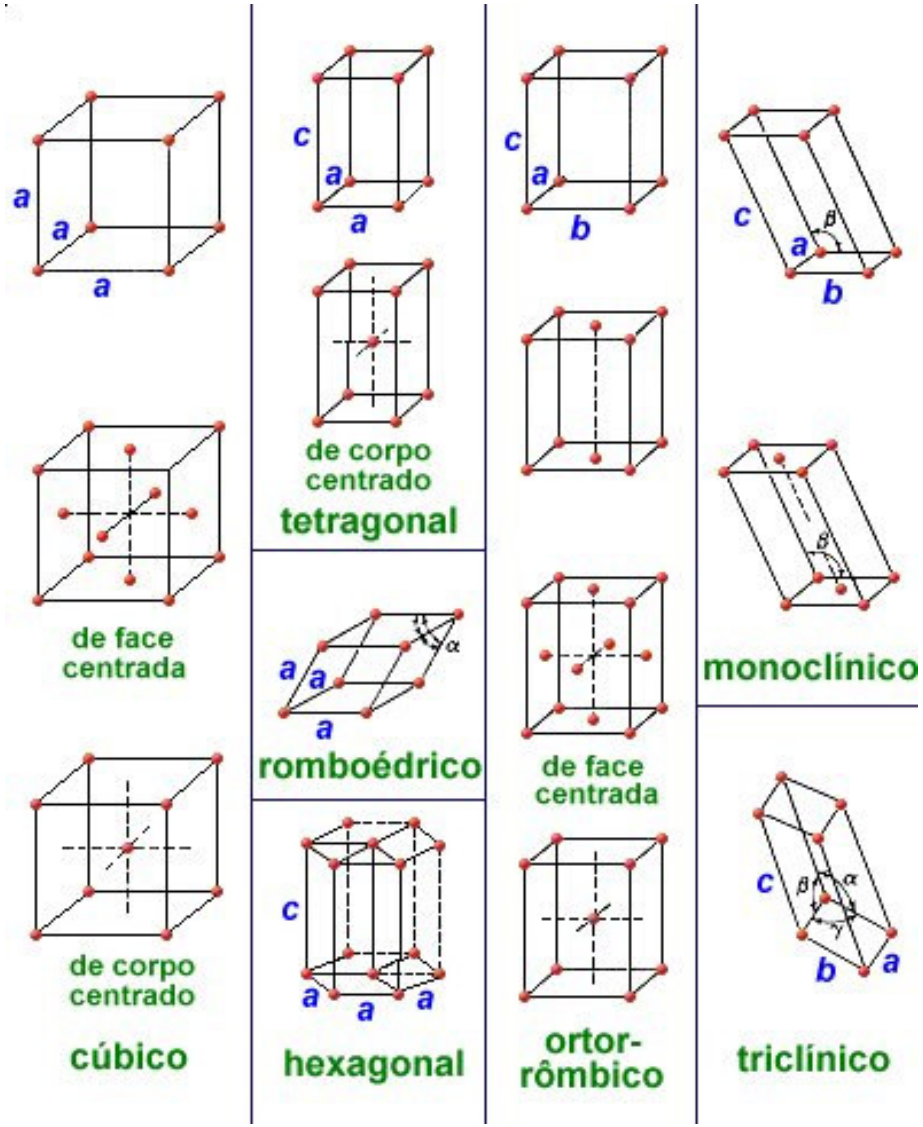


Table 3.2 Lattice Parameter Relationships and Figures Showing Unit Cell Geometries for the Seven Crystal Systems

Crystal System	*Axial Relationships*	*Interaxial Angles*	*Unit Cell Geometry*
Cubic	$a = b = c$	$\alpha = \beta = \gamma = 90°$	
Hexagonal	$a = b \neq c$	$\alpha = \beta = 90°, \gamma = 120°$	
Tetragonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90°$	
Rhombohedral	$a = b = c$	$\alpha = \beta = \gamma \neq 90°$	
Orthorhombic	$a \neq b \neq c$	$\alpha = \beta = \gamma = 90°$	
Monoclinic	$a \neq b \neq c$	$\alpha = \gamma = 90° \neq \beta$	
Triclinic	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma \neq 90°$	

AS 14 REDES DE BRAVAIS



Dos 7 sistemas cristalinos podemos identificar 14 tipos diferentes de células unitárias, conhecidas com redes de Bravais. Cada uma destas células unitárias tem certas características que ajudam a diferenciá-las das outras células unitárias. Além do mais, estas características também auxiliam na definição das propriedades de um material particular.

Characteristics of Selected Elements at 20C

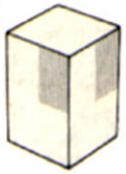
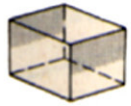
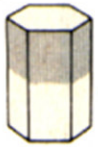
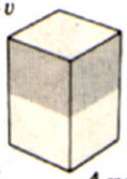
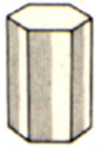
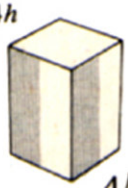
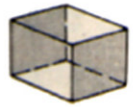
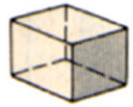
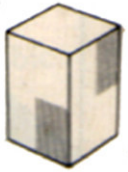
Element	Symbol	At. Weight (amu)	Density (g/cm^3)	Crystal Structure	Atomic radius (nm)
Aluminum	Al	26.98	2.71	FCC	0.143
Argon	Ar	39.95	------	------	------
Barium	Ba	137.33	3.5	BCC	0.217
Beryllium	Be	9.012	1.85	HCP	0.114
Boron	B	10.81	2.34	Rhomb	------
Bromine	Br	79.90	------	------	------
Cadmium	Cd	112.41	8.65	HCP	0.149
Calcium	Ca	40.08	1.55	FCC	0.197
Carbon	C	12.011	2.25	Hex	0.071
Cesium	Cs	132.91	1.87	BCC	0.265
Chlorine	Cl	35.45	------	------	------
Chromium	Cr	52.00	7.19	BCC	0.125
Cobalt	Co	58.93	8.9	HCP	0.125
Copper	Cu	63.55	8.94	FCC	0.128
Flourine	F	19.00	------	------	------
Gallium	Ga	69.72	5.90	Ortho.	0.122
Germanium	Ge	72.59	5.32	Dia. cubic	0.122
Gold	Au	196.97	19.32	FCC	0.144
Helium	He	4.003	------	------	------
Hydrogen	H	1.008	------	------	------

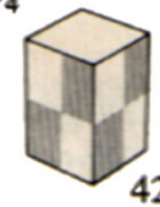
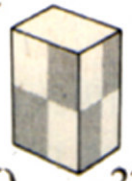
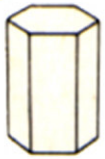
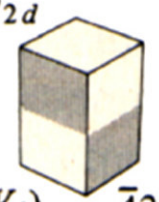
Adapted from Table, "Characteristics of Selected Elements", inside front cover, *Callister 6e.*

POINT AND SPACE GROUPS OF BRAVAIS LATTICES AND CRYSTAL STRUCTURES

	BRAVAIS LATTICE (BASIS OF SPHERICAL SYMMETRY)	CRYSTAL STRUCTURE (BASIS OF ARBITRARY SYMMETRY)
Number of point groups:	7 ("the 7 crystal systems")	32 ("the 32 crystallographic point groups")
Number of space groups:	14 ("the 14 Bravais lattices")	230 ("the 230 space groups")

THE NONCUBIC CRYSTALLOGRAPHIC POINT GROUPS[a]

SCHOEN-FLIES	HEXAGONAL	TETRAGONAL	TRIGONAL	ORTHO-RHOMBIC	MONOCLINIC	TRICLINIC	INTER-NATIONAL
C_n	C_6  6	C_4  4	C_3  3		C_2  2	C_1  1	n
C_{nv}	C_{6v}  $6mm$	C_{4v}  $4mm$	C_{3v}  $3m$	C_{2v}  $2mm$			nmm (n even) nm (n odd)
C_{nh}	C_{6h}  $6/m$	C_{4h}  $4/m$			C_{2h}  $2/m$		n/m
	C_{3h}  $\bar{6}$				C_{1h} ($\bar{2}$)  m		$\bar{n}$
S_n		S_4  $\bar{4}$	S_6  (C_{3i}) $\bar{3}$			S_2  (C_i) $\bar{1}$	

D_n	D_6  622	D_4  422	D_3  32	D_2  (V) 222			$n22$ (n even) $n2$ (n odd)
D_{nh}	D_{6h}  $6/mmm$	D_{4h}  $4/mmm$		D_{2h} (mmm)  (V_h) $2/mmm$			$\frac{n}{m}\frac{2}{m}\frac{2}{m}$ (n/mmm)
	D_{3h}  $\bar{6}2m$						$\bar{n}2m$ (n even) $\bar{n}\frac{2}{m}$ (n odd)
D_{nd}		D_{2d}  (V_d) $\bar{4}2m$	D_{3d} $(\bar{3}m)$  $\bar{3}\frac{2}{m}$				

ELEMENTS WITH THE MONATOMIC FACE-CENTERED CUBIC CRYSTAL STRUCTURE

ELEMENT	a (Å)	ELEMENT	a (Å)	ELEMENT	a (Å)
Ar	5.26 (4.2 K)	Ir	3.84	Pt	3.92
Ag	4.09	Kr	5.72 (58 K)	δ-Pu	4.64
Al	4.05	La	5.30	Rh	3.80
Au	4.08	Ne	4.43 (4.2 K)	Sc	4.54
Ca	5.58	Ni	3.52	Sr	6.08
Ce	5.16	Pb	4.95	Th	5.08
β-Co	3.55	Pd	3.89	Xe (58 K)	6.20
Cu	3.61	Pr	5.16	Yb	5.49

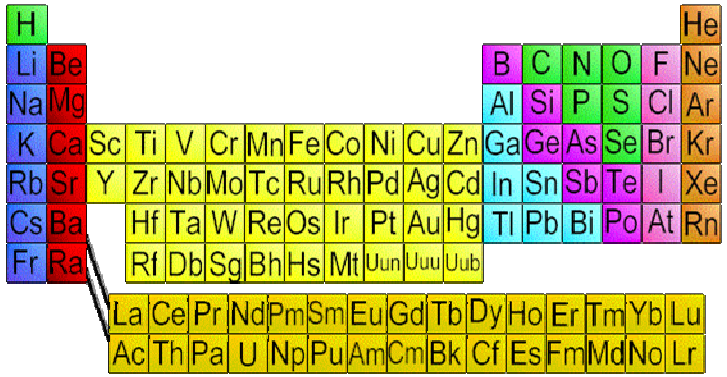
ELEMENTS WITH THE MONATOMIC BODY-CENTERED CUBIC CRYSTAL STRUCTURE

ELEMENT	a (Å)	ELEMENT	a (Å)	ELEMENT	a (Å)
Ba	5.02	Li	3.49 (78 K)	Ta	3.31
Cr	2.88	Mo	3.15	Tl	3.88
Cs	6.05 (78 K)	Na	4.23 (5 K)	V	3.02
Fe	2.87	Nb	3.30	W	3.16
K	5.23 (5 K)	Rb	5.59 (5 K)		

SOME COMPOUNDS WITH THE ZINCBLENDE STRUCTURE

CRYSTAL	a (Å)	CRYSTAL	a (Å)	CRYSTAL	a (Å)
CuF	4.26	ZnS	5.41	AlSb	6.13
CuCl	5.41	ZnSe	5.67	GaP	5.45
CuBr	5.69	ZnTe	6.09	GaAs	5.65
CuI	6.04	CdS	5.82	GaSb	6.12
AgI	6.47	CdTe	6.48	InP	5.87
BeS	4.85	HgS	5.85	InAs	6.04
BeSe	5.07	HgSe	6.08	InSb	6.48
BeTe	5.54	HgTe	6.43	SiC	4.35
MnS (red)	5.60	AlP	5.45		
MnSe	5.82	AlAs	5.62		

Dream: Atom by Atom Engineering



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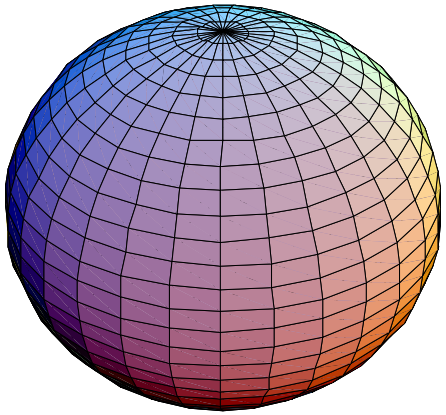


$$V = \frac{4\pi}{3} R^3$$

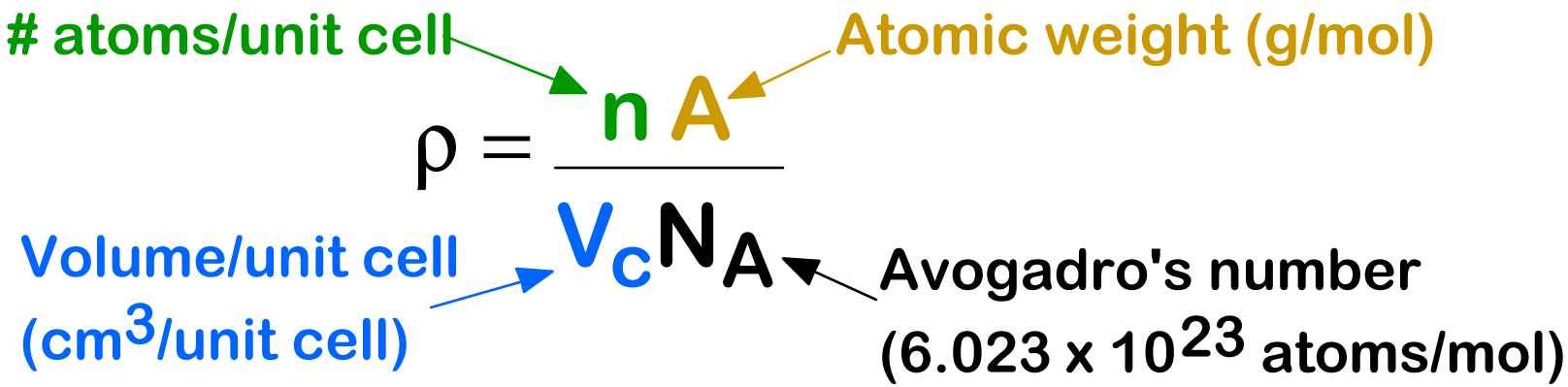
$$S = 4\pi R^2$$

$$\frac{S}{V} = \frac{3}{R}$$

Há muito espaço lá embaixo

- Uma esfera de ferro, de um kilograma de massa, possui um raio de cerca de 31 milímetros.
- A mesma massa de Fe pode ser distribuída em trinta mil esferas de 1 mm de raio, com uma superfície total de 0,38 m^2.
- Ou ainda, em trinta mil bilhões de esferas de 1 μm de raio, com uma superfície total de 380 m^2.
- Ou ainda, em trinta mil bilhões de bilhões de esferas de 1 nm de raio, com uma superfície total de 380.000

THEORETICAL DENSITY, ρ



Example: Copper

Data from Table inside front cover of Callister (see next slide):

- crystal structure = FCC: 4 atoms/unit cell
- atomic weight = 63.55 g/mol (1 amu = 1 g/mol)
- atomic radius R = 0.128 nm (1 nm = 10^{-7}cm)

$V_C = a^3$; For FCC, $a = 4R/\sqrt{2}$; $V_C = 4.75 \times 10^{-23} cm^3$

Result: theoretical $\rho_{Cu} = 8.89$ g/cm^3

Compare to actual: $\rho_{Cu} = 8.94$ g/cm^3

DENSITIES OF MATERIAL CLASSES

ρ_{metals} $\rho_{ceramics}$ $\rho_{polymers}$

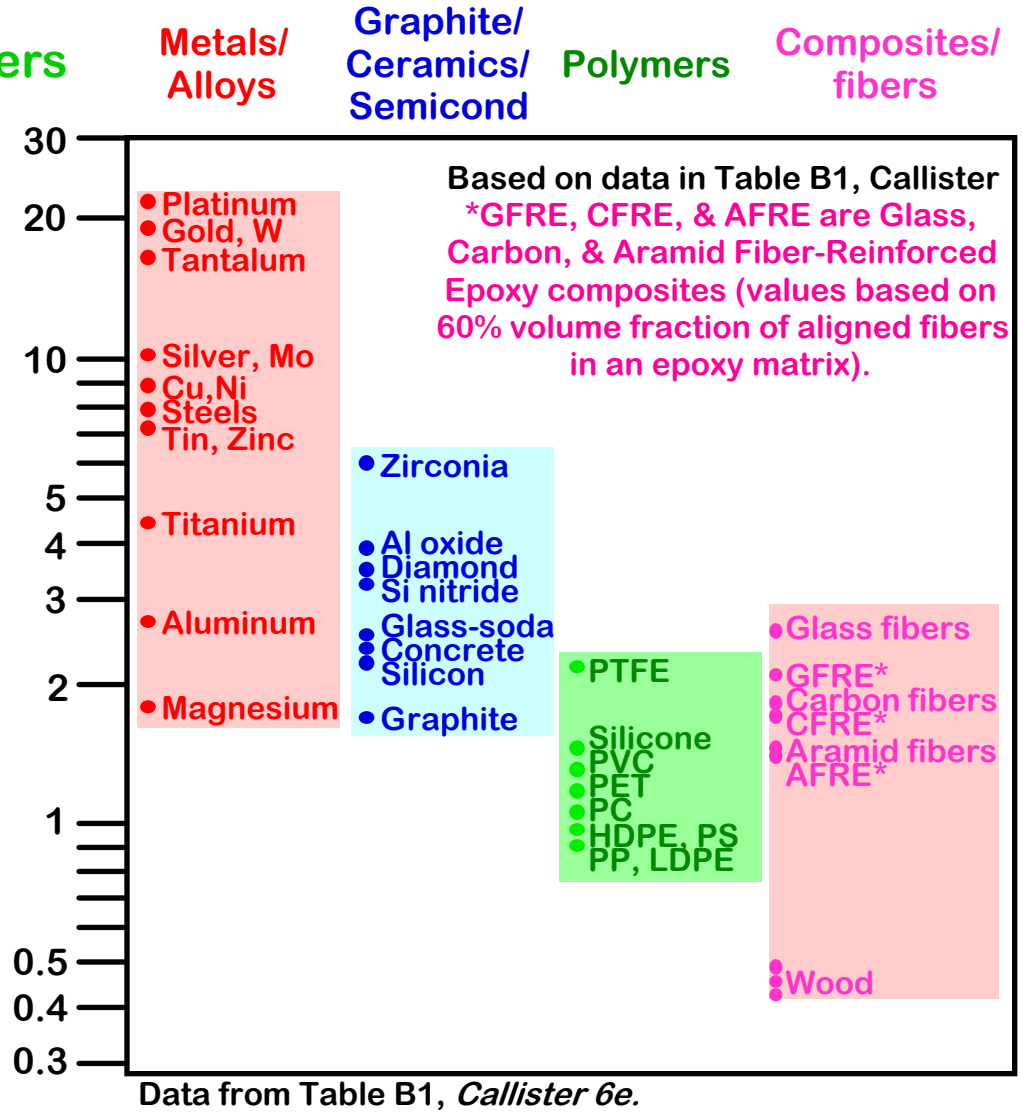
Why?

Metals have...
- close-packing (metallic bonding)
- large atomic mass

Ceramics have...
- less dense packing (covalent bonding)
- often lighter elements

Polymers have...
- poor packing (often amorphous)
- lighter elements (C,H,O)

Composites have...
- intermediate values



Data from Table B1, *Callister 6e.*

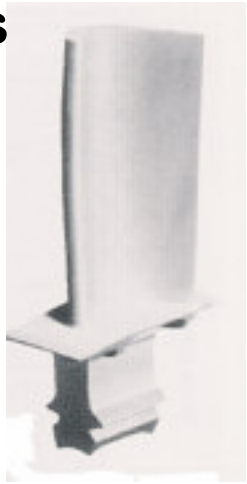
CRYSTALS AS BUILDING BLOCKS

- ***Some*** **engineering applications require single crystals:**
  --diamond single crystals for abrasives

(Courtesy Martin Deakins, GE Superabrasives, Worthington, OH. Used with permission.)

--turbine blades

Fig. 8.30(c), *Callister 6e.* (Fig. 8.30(c) courtesy of Pratt and Whitney).



- **Crystal properties reveal features of atomic structure.**

  --Ex: Certain crystal planes in quartz fracture more easily than others.

(Courtesy P.M. Anderson)

POLYCRYSTALS

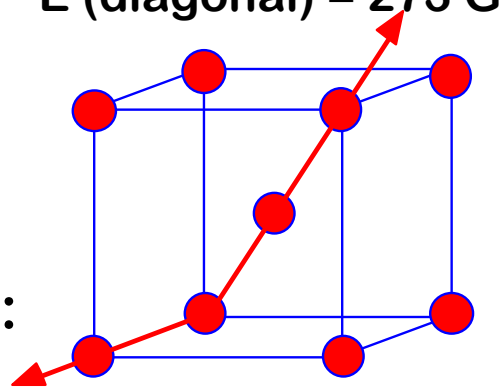
- ***Most*** **engineering materials are polycrystals.**

Adapted from Fig. K, color inset pages of *Callister 6e*.
(Fig. K is courtesy of Paul E. Danielson, Teledyne Wah Chang Albany)

- **Nb-Hf-W plate with an electron beam weld.**
- **Each "grain" is a single crystal.**
- **If crystals are randomly oriented,**
  overall component properties are not directional.
- **Crystal sizes typ. range from 1 nm to 2 cm**
  (i.e., from a few to millions of atomic layers).

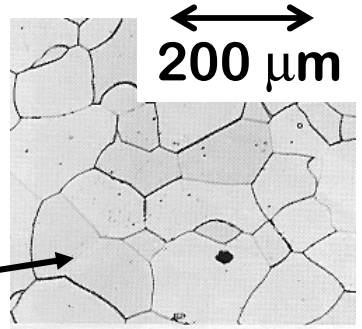
SINGLE VS POLYCRYSTALS

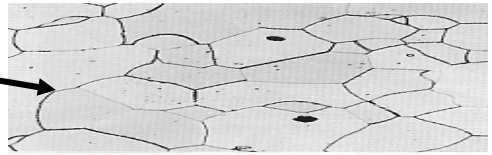
- **Single Crystals**
  - -Properties vary with direction: anisotropic.
  - -Example: the modulus of elasticity (E) in BCC iron:



Data from Table 3.3, *Callister 6e*. (Source of data is R.W. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 3rd ed., John Wiley and Sons, 1989.)

- **Polycrystals**
  - -Properties may/may not vary with direction.
  - -If grains are randomly oriented: isotropic.
    ($E_{poly\ iron}$ = 210 GPa)
  - -If grains are textured, anisotropic.

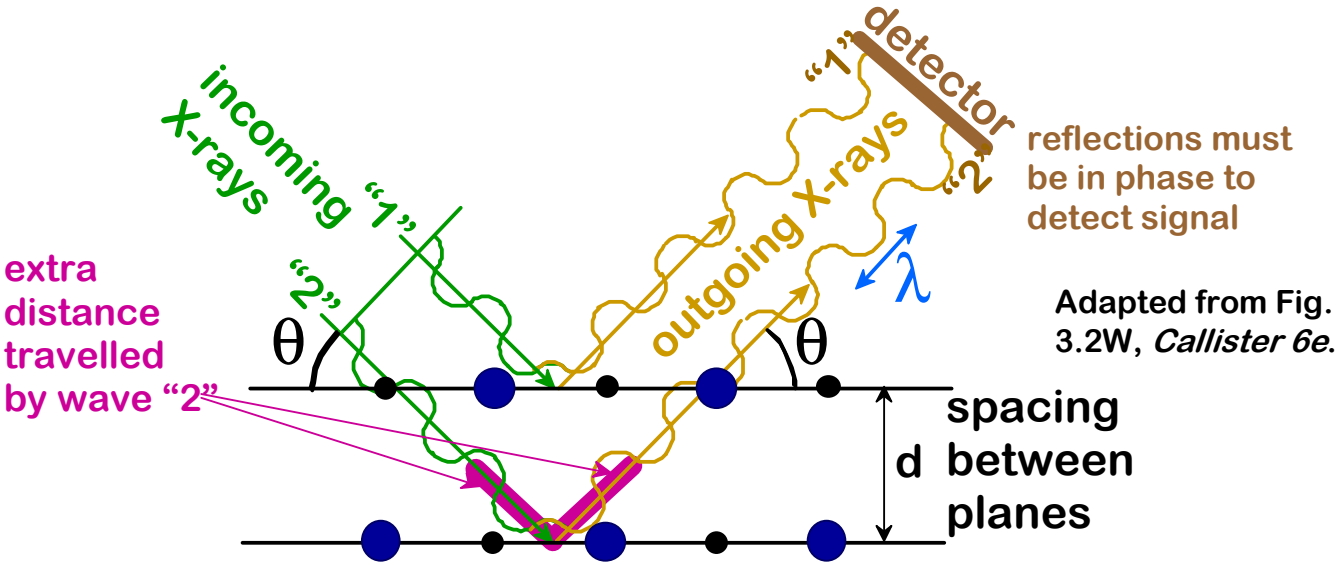




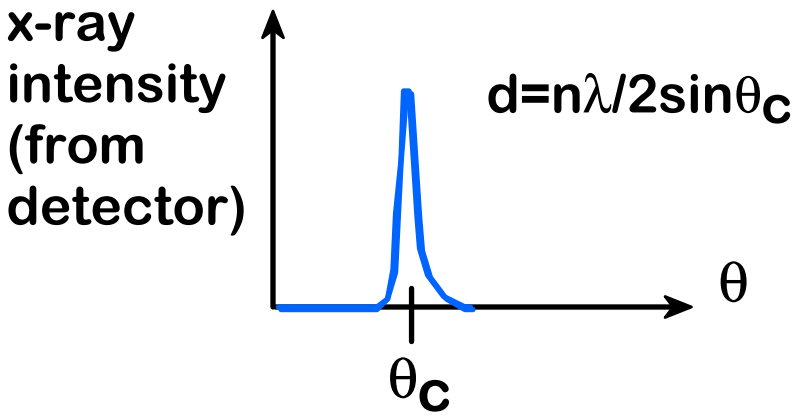
Adapted from Fig. 4.12(b), *Callister 6e*. (Fig. 4.12(b) is courtesy of L.C. Smith and C. Brady, the National Bureau of Standards, Washington, DC [now the National Institute of Standards and Technology, Gaithersburg, MD].)

X-RAYS TO CONFIRM CRYSTAL STRUCTURE

- **Incoming X-rays diffract from crystal planes.**

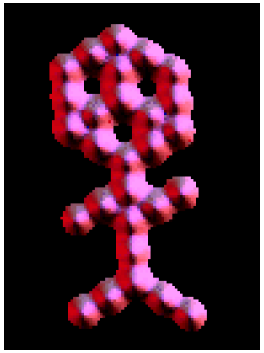


- **Measurement of:**
  Critical angles, θ_c, for X-rays provide atomic spacing, d.

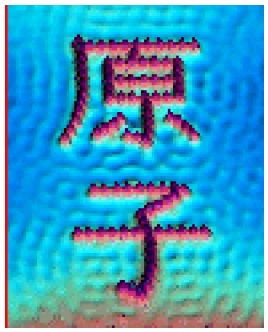


SCANNING TUNNELING MICROSCOPY

- **Atoms can be arranged and imaged!**



Carbon monoxide molecules arranged on a platinum (111) surface.

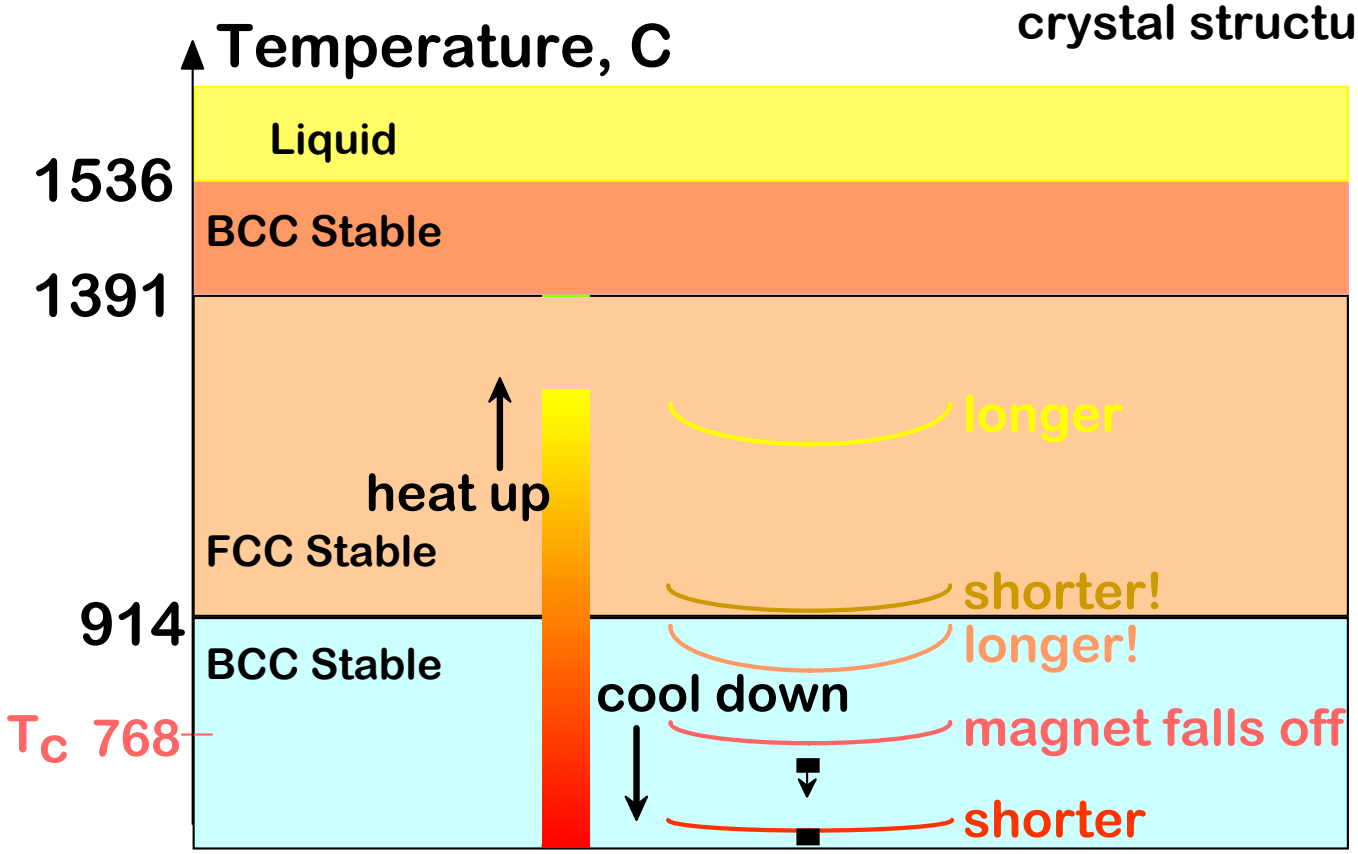


Photos produced from the work of C.P. Lutz, Zeppenfeld, and D.M. Eigler. Reprinted with permission from International Business Machines Corporation, copyright 1995.

Iron atoms arranged on a copper (111) surface. These Kanji characters represent the word "atom".

DEMO: HEATING AND COOLING OF AN IRON WIRE

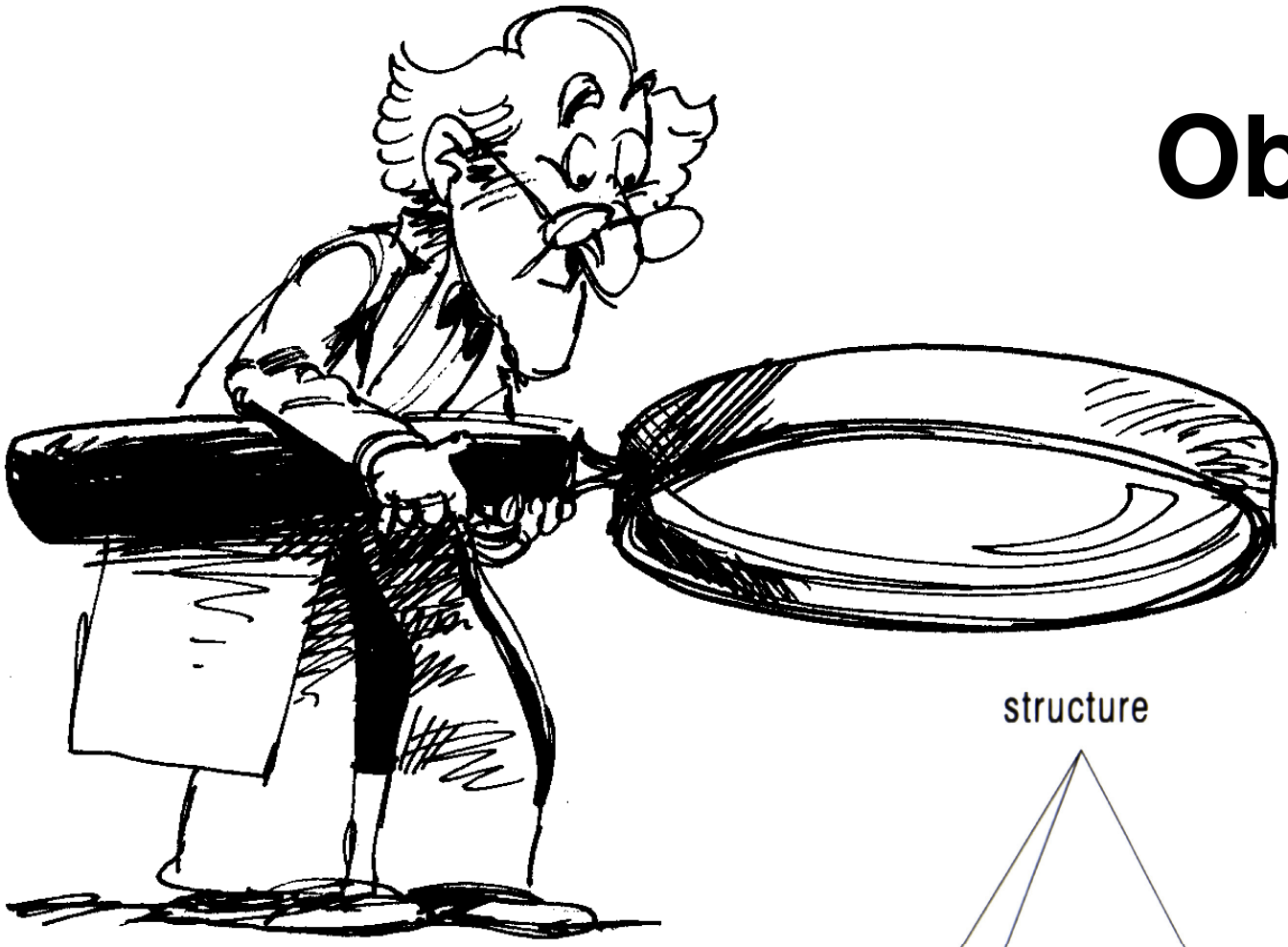
- **Demonstrates "polymorphism"** ← The same atoms can have more than one crystal structure.



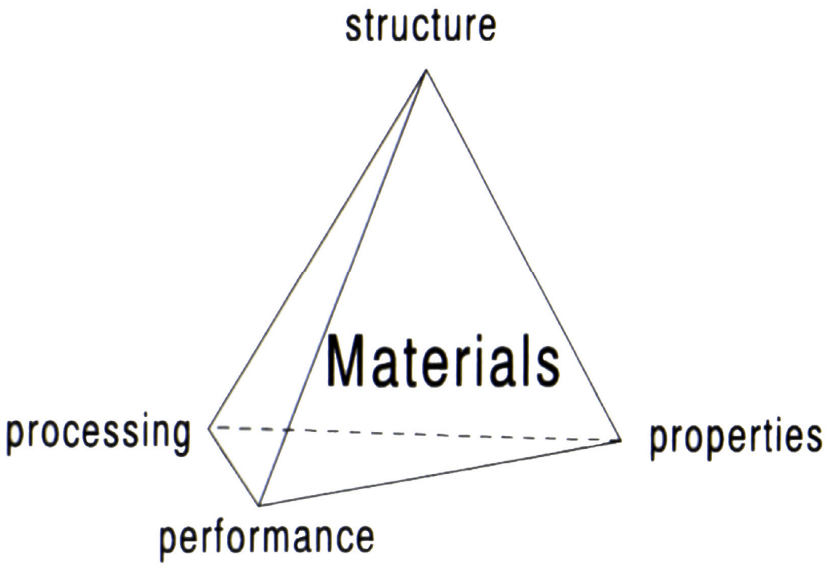
SUMMARY

- Atoms may assemble into crystalline or amorphous structures.
- We can predict the density of a material, provided we know the atomic weight, atomic radius, and crystal geometry (e.g., FCC, BCC, HCP).
- Material properties generally vary with single crystal orientation (i.e., they are anisotropic), but properties are generally non-directional (i.e., they are isotropic) in polycrystals with randomly oriented grains.

Até aqui, tudo bem

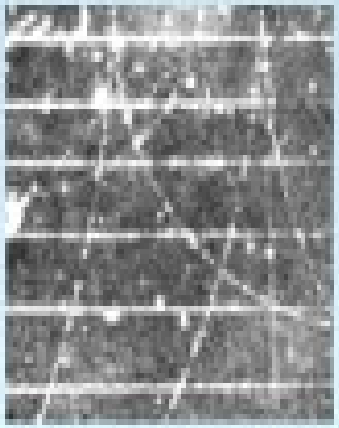


Obrigado !



Prof. Aguinaldo M Severino

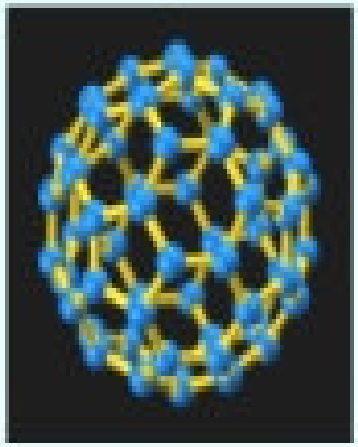
Physics



Engineering

Materials Science

Chemistry

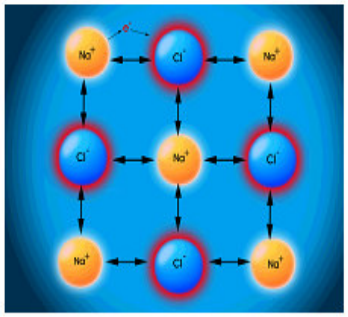


Mathematics

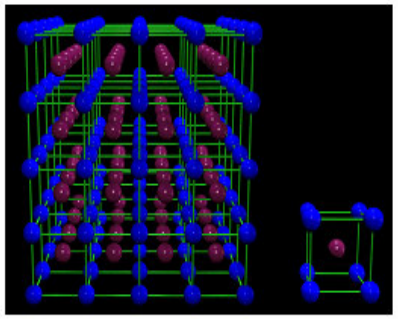
$$\frac{\partial C}{\partial t} = D \cdot \left[\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2} \right]$$

Materials Science ⇨ Bridge between Natural Science and Engineering Sciences

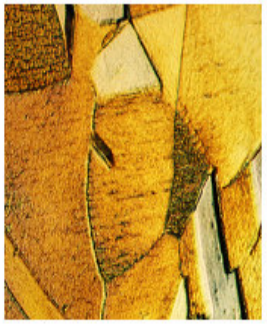
Atomic bonding



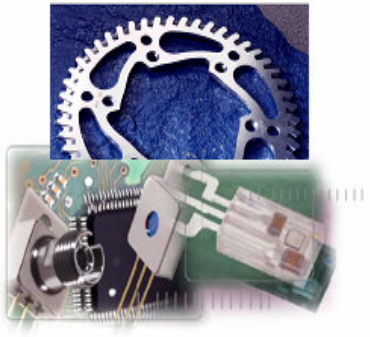
Crystal structure



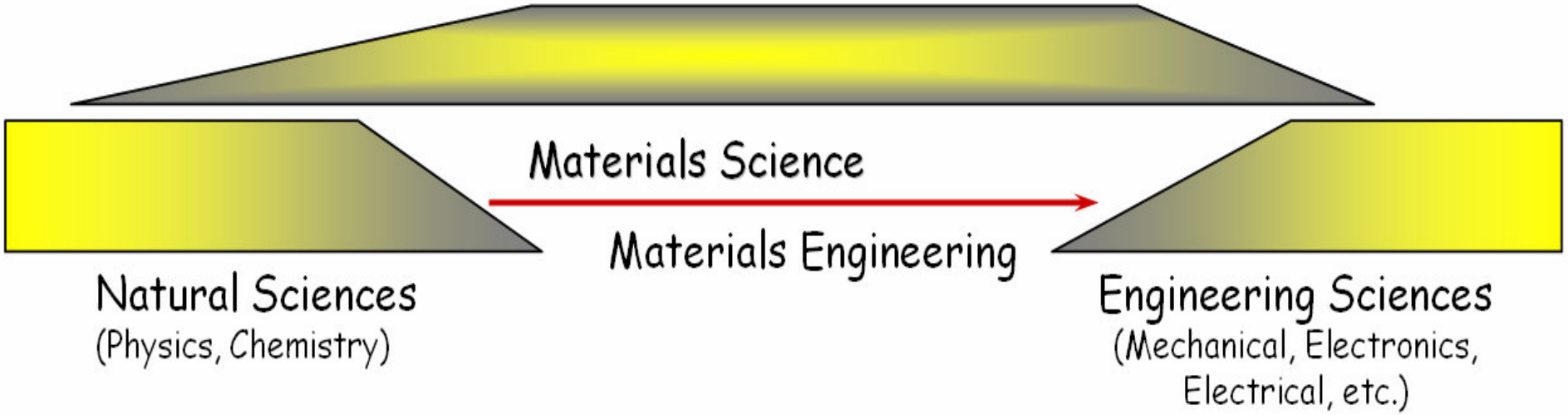
Microstructure



Construction Part



Å	nm			µm			mm	cm		m	10m
10^{-10}	10^{-9}	10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	10^{0}	10^{1}
Atom	Molecule	Protein	Light wave		Hair thickness	Nerve tissue		Handy		Auto	
Crystal structure		Virus		Cell		Blood vessel					Airplane



PERIODIC TABLE

Atomic Properties of the Elements

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Physics Laboratory
physics.nist.gov

Standard Reference Data Program
www.nist.gov/srd

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum	c	299 792 458 m s^{-1}	(exact)
Planck constant	h	6.6261×10^{-34} J s	($\hbar = h/2\pi$)
elementary charge	e	1.6022×10^{-19} C	
electron mass	m_e	9.1094×10^{-31} kg	
	$m_e c^2$	0.5110 MeV	
proton mass	m_p	1.6726×10^{-27} kg	
fine-structure constant	α	1/137.036	
Rydberg constant	R_∞	10 973 732 m^{-1}	
	$R_\infty c$	$3.289\,84 \times 10^{15}$ Hz	
	$R_\infty hc$	13.6057 eV	
Boltzmann constant	k	1.3807×10^{-23} J K^{-1}	

Solids
Liquids
Gases
Artificially Prepared

Group: IA | IIA | IIIA | IVA | VA | VIA | VIIA | VIIIA | IB | IIB | IIIB | IVB | VB | VIB | VIIB | VIII | VIII

Period: 1 | 2 | 3 | 4 | 5 | 6 | 7

Period	IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA			IB	IIB	IIIB	IVB	VB	VIB	VIIB	VIII
1	1 $^2S_{1/2}$ **H** Hydrogen 1.00794 1s 13.5984																	2 $^1S_0$ **He** Helium 4.00260 $1s^2$ 24.5874
2	3 $^2S_{1/2}$ **Li** Lithium 6.941 $1s^22s$ 5.3917	4 $^1S_0$ **Be** Beryllium 9.01218 $1s^22s^2$ 9.3227											5 $^2P^o_{1/2}$ **B** Boron 10.811 $1s^22s^22p$ 8.2980	6 $^3P_0$ **C** Carbon 12.0107 $1s^22s^22p^2$ 11.2603	7 $^4S^o_{3/2}$ **N** Nitrogen 14.00674 $1s^22s^22p^3$ 14.5341	8 $^3P_2$ **O** Oxygen 15.9994 $1s^22s^22p^4$ 13.6181	9 $^2P^o_{3/2}$ **F** Fluorine 18.99840 $1s^22s^22p^5$ 17.4228	10 $^1S_0$ **Ne** Neon 20.1797 $1s^22s^22p^6$ 21.5646
3	11 $^2S_{1/2}$ **Na** Sodium 22.98977 [Ne]3s 5.1391	12 $^1S_0$ **Mg** Magnesium 24.3050 $[Ne]3s^2$ 7.6462											13 $^2P^o_{1/2}$ **Al** Aluminum 26.98154 $[Ne]3s^23p$ 5.9858	14 $^3P_0$ **Si** Silicon 28.0855 $[Ne]3s^23p^2$ 8.1517	15 $^4S^o_{3/2}$ **P** Phosphorus 30.97376 $[Ne]3s^23p^3$ 10.4867	16 $^3P_2$ **S** Sulfur 32.066 $[Ne]3s^23p^4$ 10.3600	17 $^2P^o_{3/2}$ **Cl** Chlorine 35.4527 $[Ne]3s^23p^5$ 12.9676	18 $^1S_0$ **Ar** Argon 39.948 $[Ne]3s^23p^6$ 15.7596
4	19 $^2S_{1/2}$ **K** Potassium 39.0983 [Ar]4s 4.3407	20 $^1S_0$ **Ca** Calcium 40.078 $[Ar]4s^2$ 6.1132	21 $^2D_{3/2}$ **Sc** Scandium 44.95591 $[Ar]3d4s^2$ 6.5615	22 $^3F_2$ **Ti** Titanium 47.867 $[Ar]3d^24s^2$ 6.8281	23 $^4F_{3/2}$ **V** Vanadium 50.9415 $[Ar]3d^34s^2$ 6.7462	24 $^7S_3$ **Cr** Chromium 51.9961 $[Ar]3d^54s$ 6.7665	25 $^6S_{5/2}$ **Mn** Manganese 54.93805 $[Ar]3d^54s^2$ 7.4340	26 $^5D_4$ **Fe** Iron 55.845 $[Ar]3d^64s^2$ 7.9024	27 $^4F_{9/2}$ **Co** Cobalt 58.93320 $[Ar]3d^74s^2$ 7.8810	28 $^3F_4$ **Ni** Nickel 58.6934 $[Ar]3d^84s^2$ 7.6398	29 $^2S_{1/2}$ **Cu** Copper 63.546 $[Ar]3d^{10}4s$ 7.7264	30 $^1S_0$ **Zn** Zinc 65.39 $[Ar]3d^{10}4s^2$ 9.3942	31 $^2P^o_{1/2}$ **Ga** Gallium 69.723 $[Ar]3d^{10}4s^24p$ 5.9993	32 $^3P_0$ **Ge** Germanium 72.61 $[Ar]3d^{10}4s^24p^2$ 7.8994	33 $^4S^o_{3/2}$ **As** Arsenic 74.92160 $[Ar]3d^{10}4s^24p^3$ 9.7886	34 $^3P_2$ **Se** Selenium 78.96 $[Ar]3d^{10}4s^24p^4$ 9.7524	35 $^2P^o_{3/2}$ **Br** Bromine 79.904 $[Ar]3d^{10}4s^24p^5$ 11.8138	36 $^1S_0$ **Kr** Krypton 83.80 $[Ar]3d^{10}4s^24p^6$ 13.9996
5	37 $^2S_{1/2}$ **Rb** Rubidium 85.4678 [Kr]5s 4.1771	38 $^1S_0$ **Sr** Strontium 87.62 $[Kr]5s^2$ 5.6949	39 $^2D_{3/2}$ **Y** Yttrium 88.90585 $[Kr]4d5s^2$ 6.2173	40 $^3F_2$ **Zr** Zirconium 91.224 $[Kr]4d^25s^2$ 6.6339	41 $^6D_{1/2}$ **Nb** Niobium 92.90638 $[Kr]4d^45s$ 6.7589	42 $^7S_3$ **Mo** Molybdenum 95.94 $[Kr]4d^55s$ 7.0924	43 $^6S_{5/2}$ **Tc** Technetium (98) $[Kr]4d^55s^2$ 7.28	44 $^5F_5$ **Ru** Ruthenium 101.07 $[Kr]4d^75s$ 7.3605	45 $^4F_{9/2}$ **Rh** Rhodium 102.90550 $[Kr]4d^85s$ 7.4589	46 $^1S_0$ **Pd** Palladium 106.42 $[Kr]4d^{10}$ 8.3369	47 $^2S_{1/2}$ **Ag** Silver 107.8682 $[Kr]4d^{10}5s$ 7.5762	48 $^1S_0$ **Cd** Cadmium 112.411 $[Kr]4d^{10}5s^2$ 8.9938	49 $^2P^o_{1/2}$ **In** Indium 114.818 $[Kr]4d^{10}5s^25p$ 5.7864	50 $^3P_0$ **Sn** Tin 118.710 $[Kr]4d^{10}5s^25p^2$ 7.3439	51 $^4S^o_{3/2}$ **Sb** Antimony 121.760 $[Kr]4d^{10}5s^25p^3$ 8.6084	52 $^3P_2$ **Te** Tellurium 127.60 $[Kr]4d^{10}5s^25p^4$ 9.0096	53 $^2P^o_{3/2}$ **I** Iodine 126.90447 $[Kr]4d^{10}5s^25p^5$ 10.4513	54 $^1S_0$ **Xe** Xenon 131.29 $[Kr]4d^{10}5s^25p^6$ 12.1298
6	55 $^2S_{1/2}$ **Cs** Cesium 132.90545 [Xe]6s 3.8939	56 $^1S_0$ **Ba** Barium 137.327 $[Xe]6s^2$ 5.2117		72 $^3F_2$ **Hf** Hafnium 178.49 $[Xe]4f^{14}5d^26s^2$ 6.8251	73 $^4F_{3/2}$ **Ta** Tantalum 180.9479 $[Xe]4f^{14}5d^36s^2$ 7.5496	74 $^5D_0$ **W** Tungsten 183.84 $[Xe]4f^{14}5d^46s^2$ 7.8640	75 $^6S_{5/2}$ **Re** Rhenium 186.207 $[Xe]4f^{14}5d^56s^2$ 7.8335	76 $^5D_4$ **Os** Osmium 190.23 $[Xe]4f^{14}5d^66s^2$ 8.4382	77 $^4F_{9/2}$ **Ir** Iridium 192.217 $[Xe]4f^{14}5d^76s^2$ 8.9670	78 $^3D_3$ **Pt** Platinum 195.078 $[Xe]4f^{14}5d^96s$ 8.9588	79 $^2S_{1/2}$ **Au** Gold 196.96655 $[Xe]4f^{14}5d^{10}6s$ 9.2255	80 $^1S_0$ **Hg** Mercury 200.59 $[Xe]4f^{14}5d^{10}6s^2$ 10.4375	81 $^2P^o_{1/2}$ **Tl** Thallium 204.3833 [Hg]6p 6.1082	82 $^3P_0$ **Pb** Lead 207.2 $[Hg]6p^2$ 7.4167	83 $^4S^o_{3/2}$ **Bi** Bismuth 208.98038 $[Hg]6p^3$ 7.2855	84 $^3P_2$ **Po** Polonium (209) $[Hg]6p^4$ 8.417 ?	85 $^2P^o_{3/2}$ **At** Astatine (210) $[Hg]6p^5$	86 $^1S_0$ **Rn** Radon (222) $[Hg]6p^6$ 10.7485
7	87 $^2S_{1/2}$ **Fr** Francium (223) [Rn]7s 4.0727	88 $^1S_0$ **Ra** Radium (226) $[Rn]7s^2$ 5.2784		104 $^3F_2$? **Rf** Rutherfordium (261) $[Rn]5f^{14}6d^27s^2$? 6.0 ?	105 **Db** Dubnium (262)	106 **Sg** Seaborgium (266)	107 **Bh** Bohrium (264)	108 **Hs** Hassium (269)	109 **Mt** Meitnerium (268)	110 **Uun** Ununnilium (271)	111 **Uuu** Unununium (272)	112 **Uub** Ununbium (277)		114 **Uuq** Ununquadium (289)		116 **Uuh** Ununhexium (289)		118 **Uuo** Ununoctium (293)

57 $^2D_{3/2}$ **La** Lanthanum 138.9055 $[Xe]5d6s^2$ 5.5769	58 $^1G^o_4$ **Ce** Cerium 140.116 $[Xe]4f5d6s^2$ 5.5387	59 $^4I^o_{9/2}$ **Pr** Praseodymium 140.90765 $[Xe]4f^36s^2$ 5.473	60 $^5I_4$ **Nd** Neodymium 144.24 $[Xe]4f^46s^2$ 5.5250	61 $^6H^o_{5/2}$ **Pm** Promethium (145) $[Xe]4f^56s^2$ 5.582	62 $^7F_0$ **Sm** Samarium 150.36 $[Xe]4f^66s^2$ 5.6437	63 $^8S^o_{7/2}$ **Eu** Europium 151.964 $[Xe]4f^76s^2$ 5.6704	64 $^9D^o_2$ **Gd** Gadolinium 157.25 $[Xe]4f^75d6s^2$ 6.1498	65 $^6H^o_{15/2}$ **Tb** Terbium 158.92534 $[Xe]4f^96s^2$ 5.8638	66 $^5I_8$ **Dy** Dysprosium 162.50 $[Xe]4f^{10}6s^2$ 5.9389	67 $^4I^o_{15/2}$ **Ho** Holmium 164.93032 $[Xe]4f^{11}6s^2$ 6.0215	68 $^3H_6$ **Er** Erbium 167.26 $[Xe]4f^{12}6s^2$ 6.1077	69 $^2F^o_{7/2}$ **Tm** Thulium 168.93421 $[Xe]4f^{13}6s^2$ 6.1843	70 $^1S_0$ **Yb** Ytterbium 173.04 $[Xe]4f^{14}6s^2$ 6.2542	71 $^2D_{3/2}$ **Lu** Lutetium 174.967 $[Xe]4f^{14}5d6s^2$ 5.4259
89 $^2D_{3/2}$ **Ac** Actinium (227) $[Rn]6d7s^2$ 5.17	90 $^3F_2$ **Th** Thorium 232.0381 $[Rn]6d^27s^2$ 6.3067	91 $^4K_{11/2}$ **Pa** Protactinium 231.03588 $[Rn]5f^26d7s^2$ 5.89	92 $^5L_6$ **U** Uranium 238.0289 $[Rn]5f^36d7s^2$ 6.1941	93 $^6L_{11/2}$ **Np** Neptunium (237) $[Rn]5f^46d7s^2$ 6.2657	94 $^7F_0$ **Pu** Plutonium (244) $[Rn]5f^67s^2$ 6.0262	95 $^8S^o_{7/2}$ **Am** Americium (243) $[Rn]5f^77s^2$ 5.9738	96 $^9D^o_2$ **Cm** Curium (247) $[Rn]5f^76d7s^2$ 5.9915	97 $^6H^o_{15/2}$ **Bk** Berkelium (247) $[Rn]5f^97s^2$ 6.1979	98 $^5I_8$ **Cf** Californium (251) $[Rn]5f^{10}7s^2$ 6.2817	99 $^4I^o_{15/2}$ **Es** Einsteinium (252) $[Rn]5f^{11}7s^2$ 6.42	100 $^3H_6$ **Fm** Fermium (257) $[Rn]5f^{12}7s^2$ 6.50	101 $^2F^o_{7/2}$ **Md** Mendelevium (258) $[Rn]5f^{13}7s^2$ 6.58	102 $^1S_0$ **No** Nobelium (259) $[Rn]5f^{14}7s^2$ 6.65	103 $^2P^o_{1/2}$ **Lr** Lawrencium (262) $[Rn]5f^{14}7s^27p$? 4.9 ?

Atomic Number | Ground-state Level | Symbol | Name | Atomic Weight† | Ground-state Configuration | Ionization Energy (eV)

58 $^1G^o_4$ **Ce** Cerium 140.116 $[Xe]4f5d6s^2$ 5.5387

†Based upon ^{12}C. ( ) indicates the mass number of the most stable isotope.

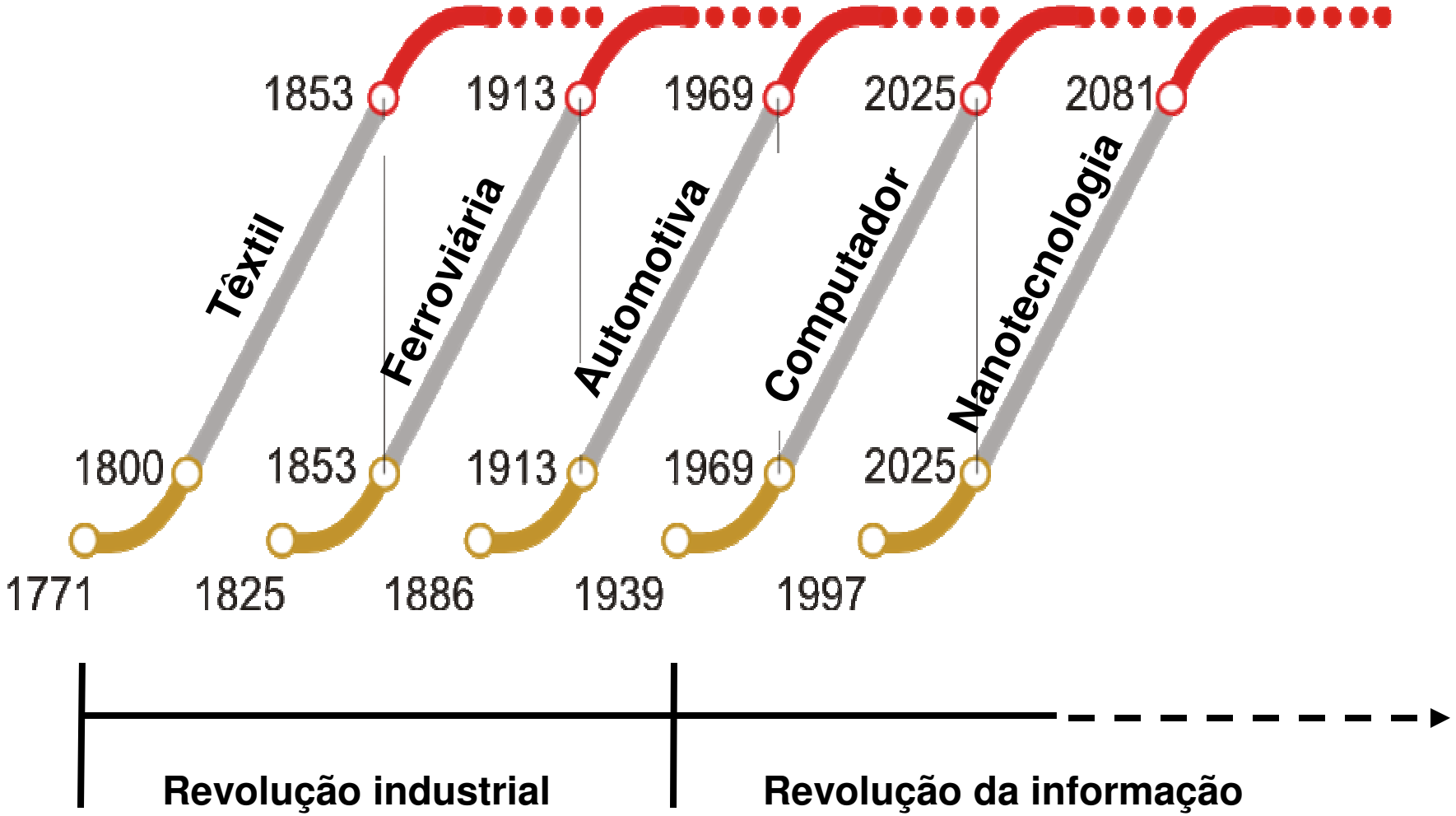
For a description of the data, visit physics.nist.gov/data

NIST SP 966 (March 2001)

MATERIAIS

- **Metals:** Materials that are normally combinations of "metallic elements". These elements, when combined, usually have electrons that are non localized and as a consequence have generic types of properties. Metals usually are good conductors of heat and electricity. Also, they are quite strong but malleable and tend to have a lustrous look when polished.
- **Ceramics:** Ceramics are generally compounds between metallic and nonmetallic elements and include such compounds as oxides, nitrides, and carbides. Typically they are insulating and resistant to high temperatures and harsh environments.
- **Plastics:** Plastics (or polymers) are generally organic compounds based upon carbon and hydrogen. They are very large molecular structures. Usually they are low density and are not stable at high temperatures.
- **Semiconductors:** Semiconductors have electrical properties intermediate between metallic conductors and ceramic insulators. Also, the electrical properties are strongly dependent upon small amounts of impurities.
- **Composites:** Composites consist of more than one material type. Fiberglass, a combination of glass and a polymer, is an example. Concrete and plywood are other familiar composites. Many new combinations include ceramic fibers in metal or polymer matrix.

FORÇAS TÉCNOLÓGICAS REVOLUCIONÁRIAS



Introdução da tecnologia

Ampla utilização

Final do crescimento rápido

Ref: Milunovich S. and Roy J.M.A.:
The Next Small Thing RC 30224705
Merril Lynch, 4 September, 2001

Aula 02

SOME COMPOUNDS WITH THE ZINCBLENDE STRUCTURE

CRYSTAL	a (Å)	CRYSTAL	a (Å)	CRYSTAL	a (Å)
CuF	4.26	ZnS	5.41	AlSb	6.13
CuCl	5.41	ZnSe	5.67	GaP	5.45
CuBr	5.69	ZnTe	6.09	GaAs	5.65
CuI	6.04	CdS	5.82	GaSb	6.12
AgI	6.47	CdTe	6.48	InP	5.87
BeS	4.85	HgS	5.85	InAs	6.04
BeSe	5.07	HgSe	6.08	InSb	6.48
BeTe	5.54	HgTe	6.43	SiC	4.35
MnS (red)	5.60	AlP	5.45		
MnSe	5.82	AlAs	5.62		