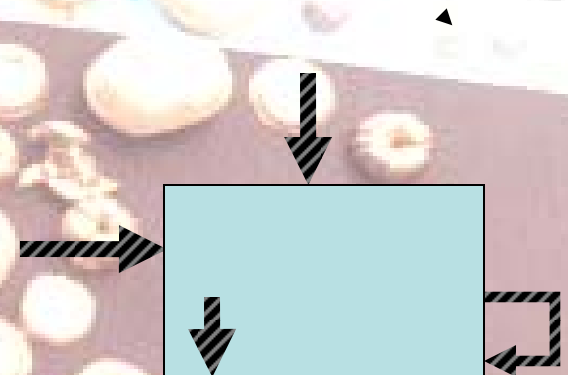




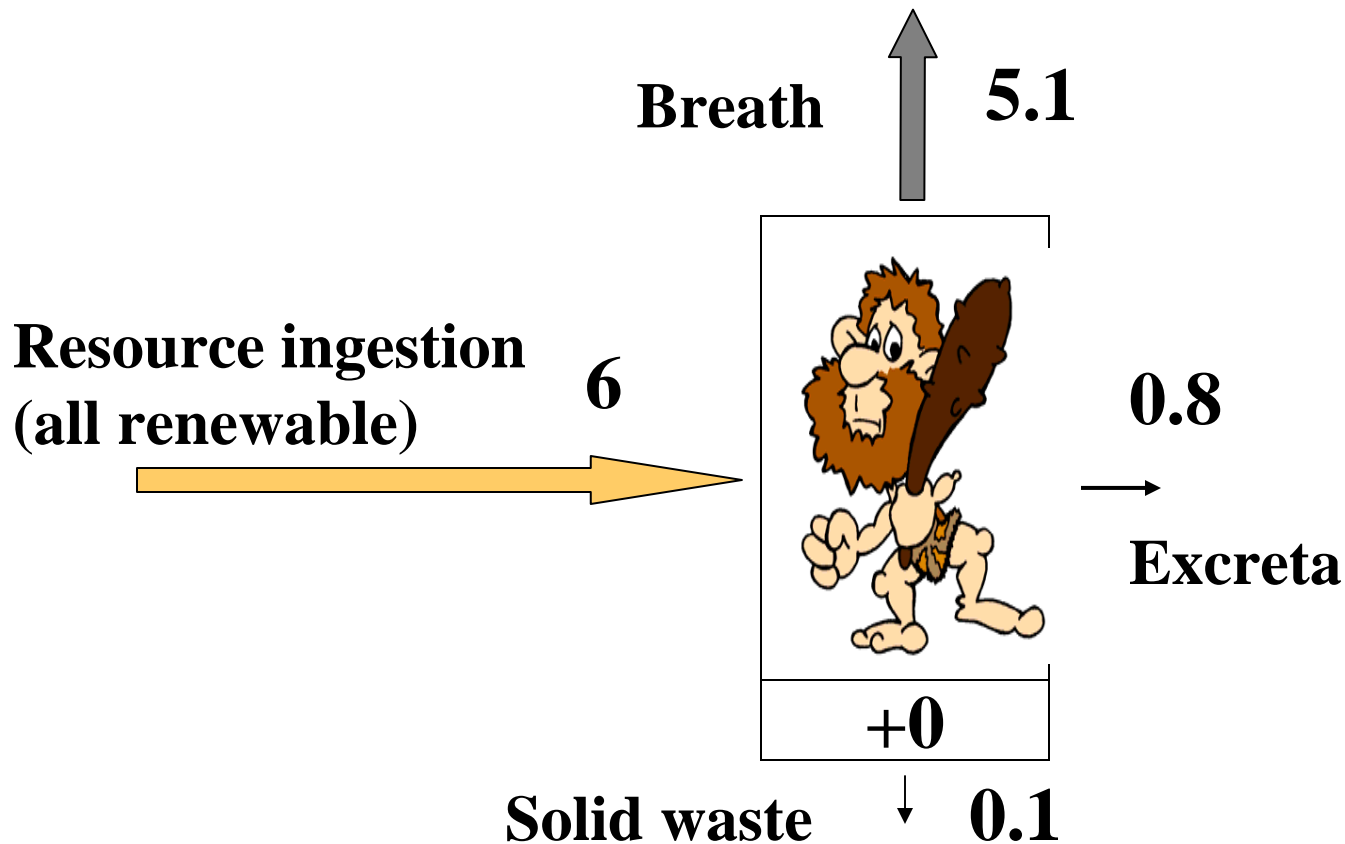
# Are Non-Renewable Resources Critical?

Thomas E. Graedel

Yale University

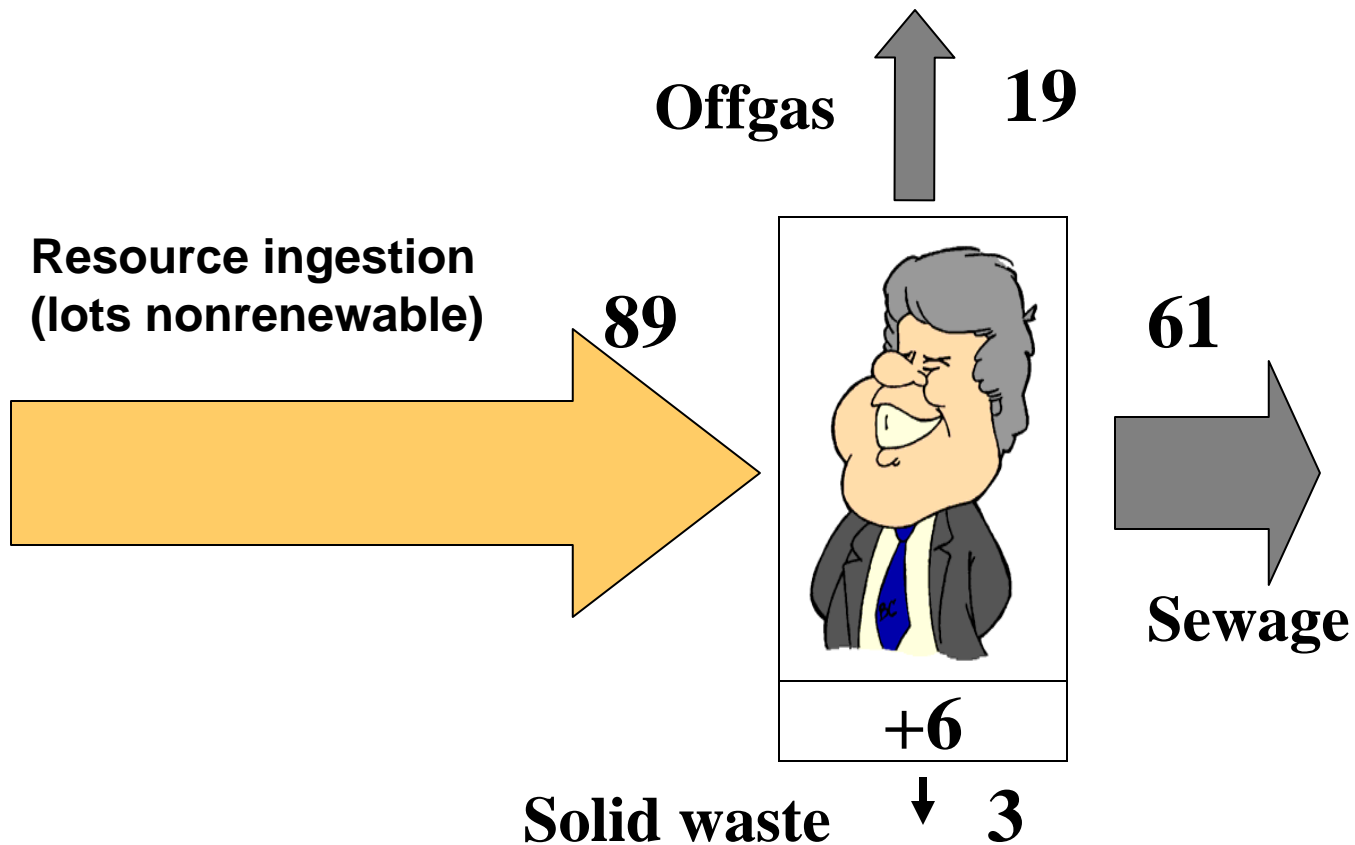


# Total Material Consumption: Neolithic Human



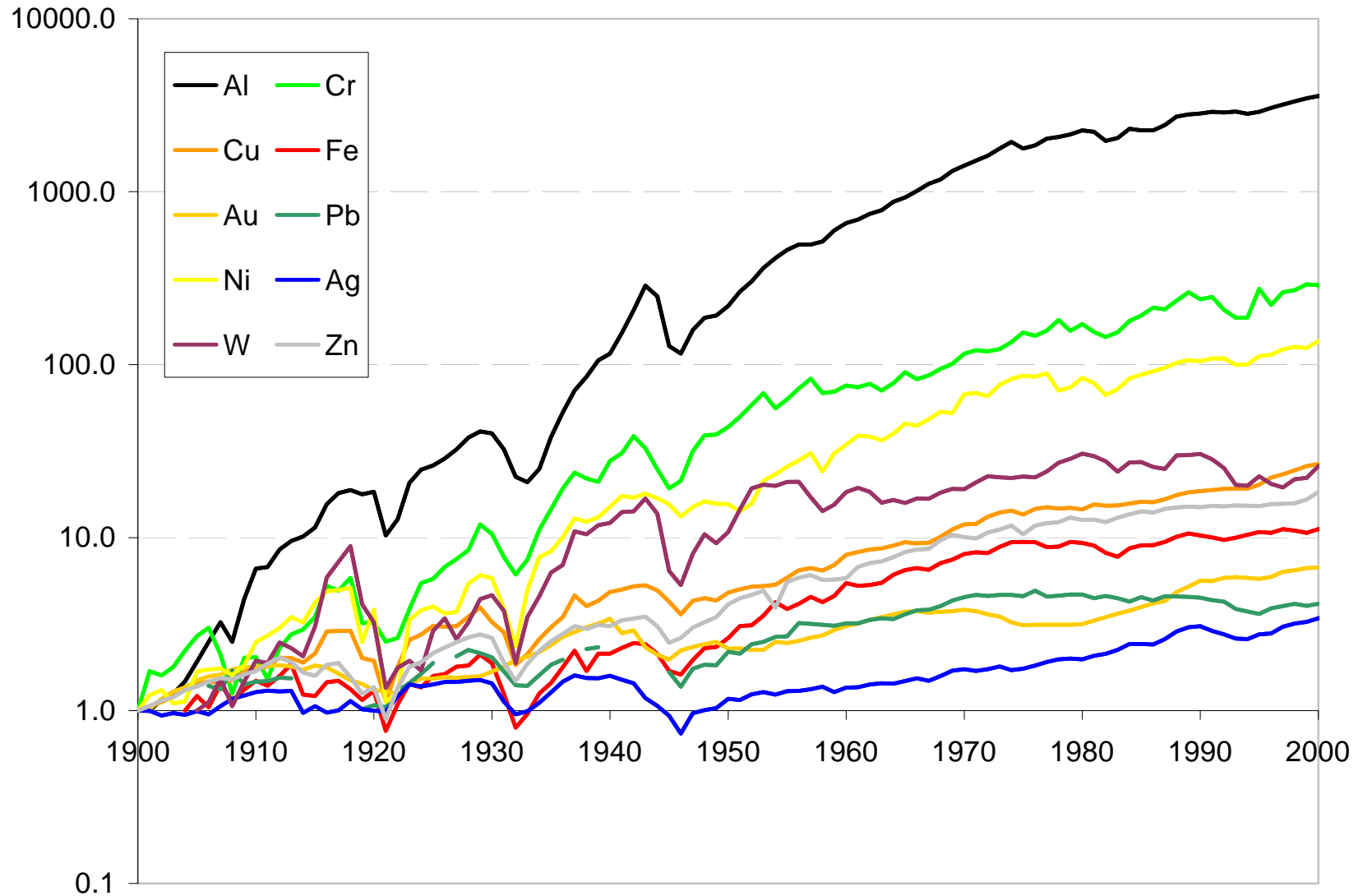
Unit: tonnes/cap-yr

# Total Material Consumption: Modern Human

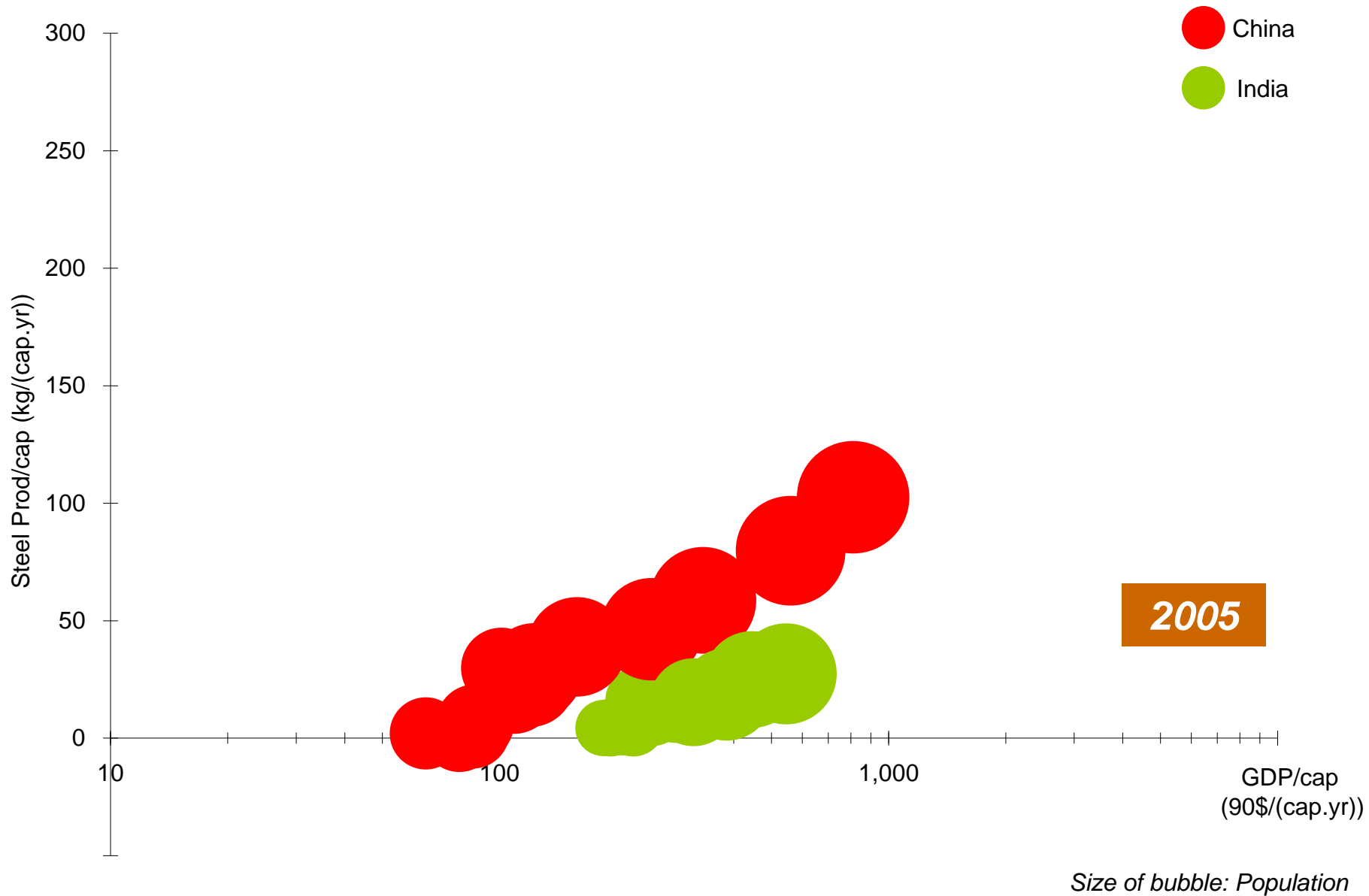


Unit: tonnes/cap-yr

# Global 20<sup>th</sup> Century Metal Use



# Crude Steel Production in China and India, 1945-2005



# Metal Linkages in the New Mineralogy

[1980s]

1	2											18					
1 H 1.0079																	18 Ar 39.948
3 Li 6.941	4 Be 9.0122											36 Kr 83.80					
11 Na 22.990	12 Mg 24.305											54 Xe 131.29					
19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.887	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	32 Ge 72.64	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.80
37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	(90)	44 Ru 101.07	45 Rh 101.91	46 Pd 106.4	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.710	51 Sb 121.757	52 Te 127.6	53 I 126.905	54 Xe 131.29
55 Cs 132.91	56 Ba 137.33	57-71 *	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 196.967	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)	89-103 Ac											110 Dn 289				
57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.925	66 Dy 162.5	67 Ho 164.930	68 Er 167.259	69 Tm 168.934	70 Yb 173.054	71 Lu 174.967			
89 Ac (117)	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 (260)			

11 Elements

+4 Elements

+45 Elements  
(Potential)

[1990s]

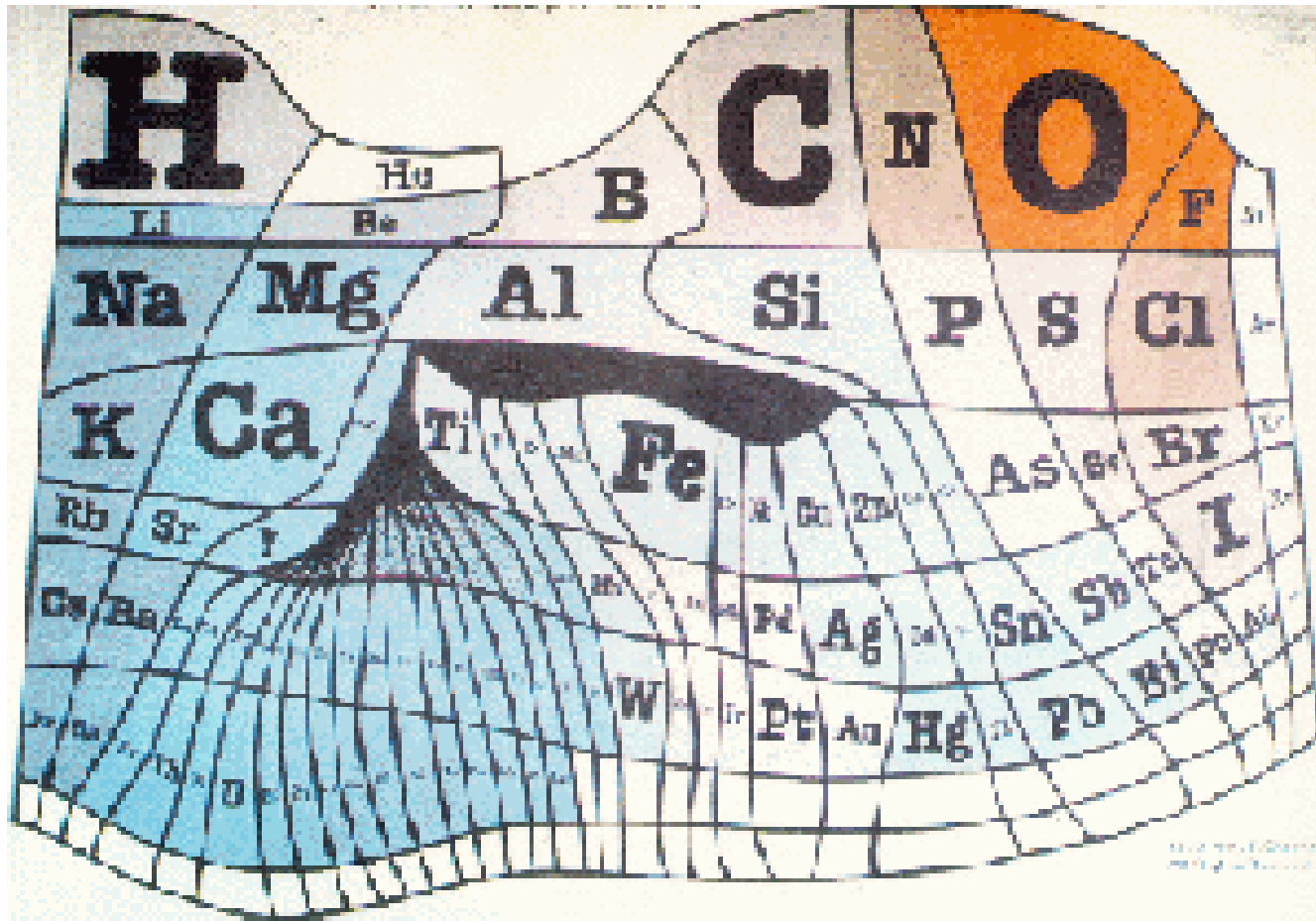
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57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.925	66 Dy 162.5	67 Ho 164.930	68 Er 167.259	69 Tm 168.934	70 Yb 173.054	71 Lu 174.967			
89 Ac (117)	90 Th 232.04	91 Pa 231.04	92 U 238.03	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 (260)			

[2000s]

1	2											18					
1 H 1.0079																	18 Ar 39.948
3 Li 6.941	4 Be 9.0122											36 Kr 83.80					
11 Na 22.990	12 Mg 24.305											54 Xe 131.29					
19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.887	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.38	31 Ga 69.723	32 Ge 72.64	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.80
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Source: T. McManus, Intel Corp., 2006

# Periodic Table According to Atomic Abundance in Earth's Crust



# The Central Question

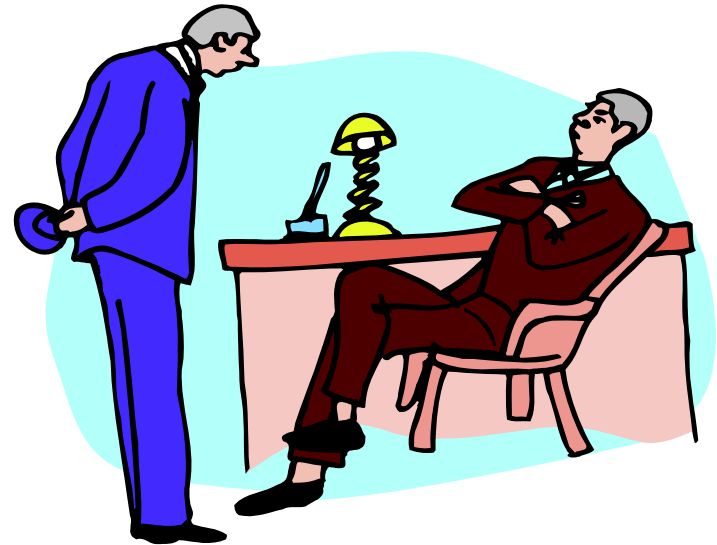
People agree we are getting close to “peak oil” – the year in which oil production will hit a peak and then decline. Should we expect “peak metals” in our future?

# Evaluating the Criticality of Materials

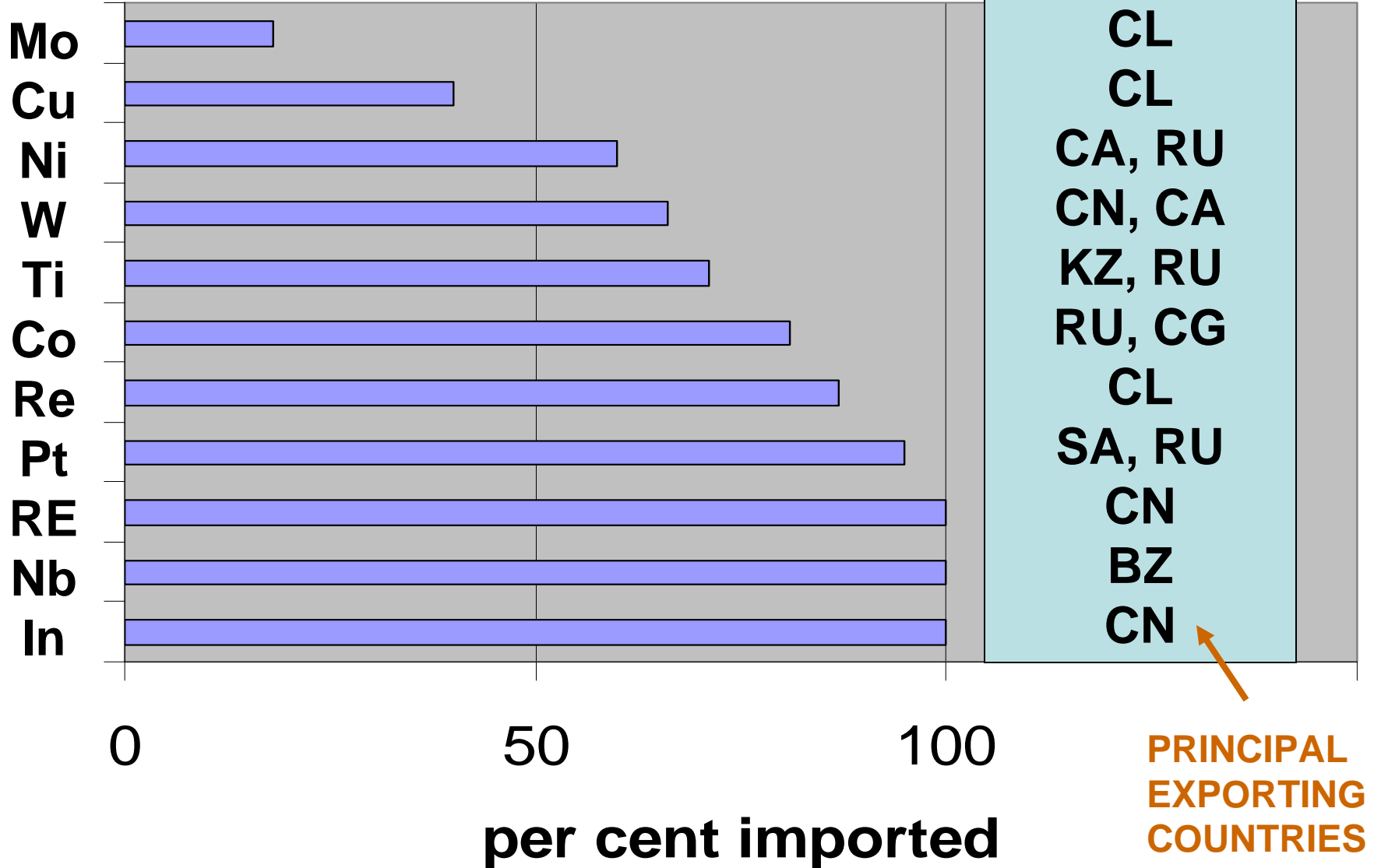
# The First Dimension of Criticality

## Supply risk

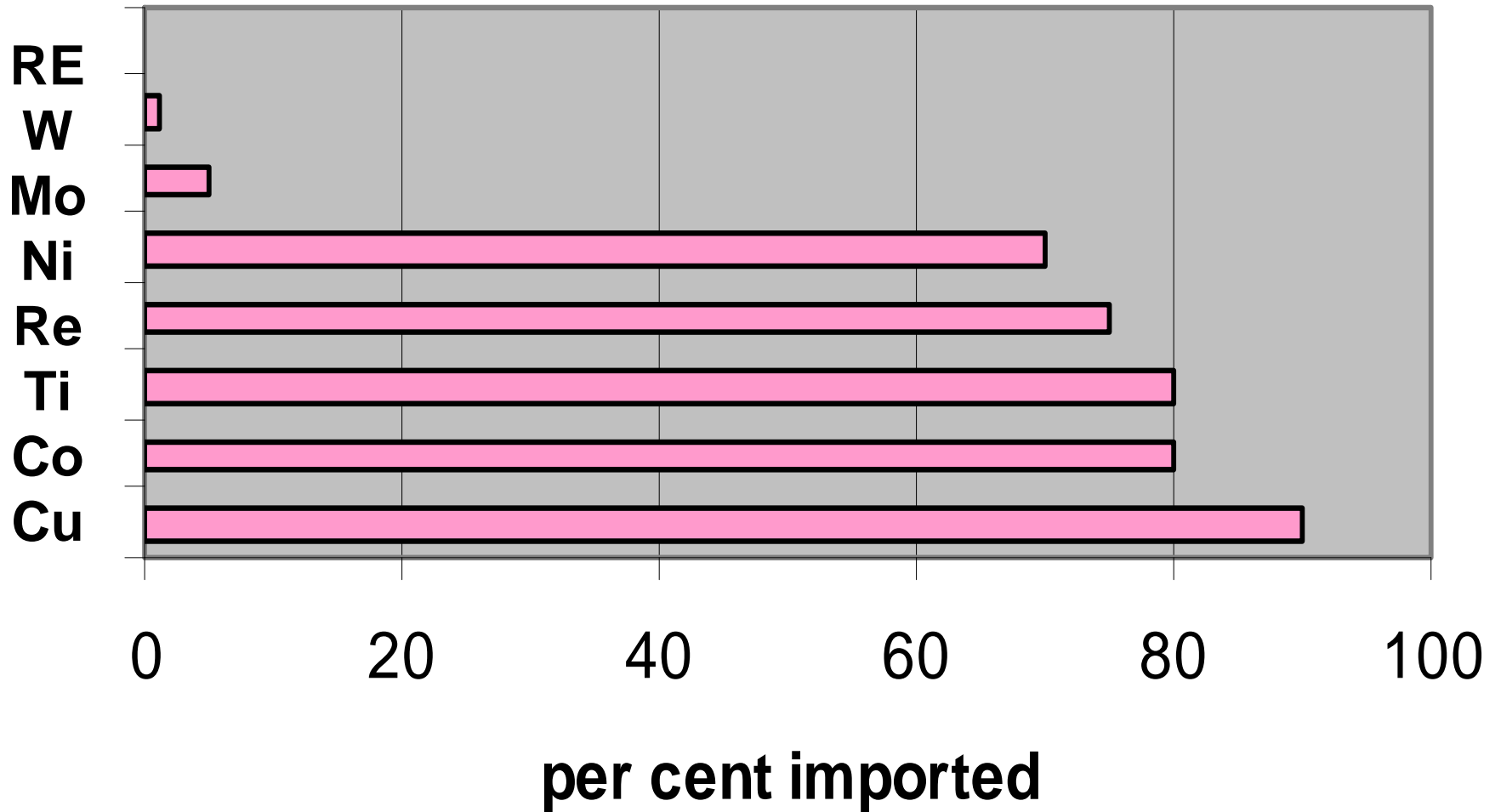
- **Geologic availability**
- **Regulatory availability**
- **Social availability**
- **Technical availability**
- **Geopolitical availability**
- **Market availability**



# US Resource Dependencies

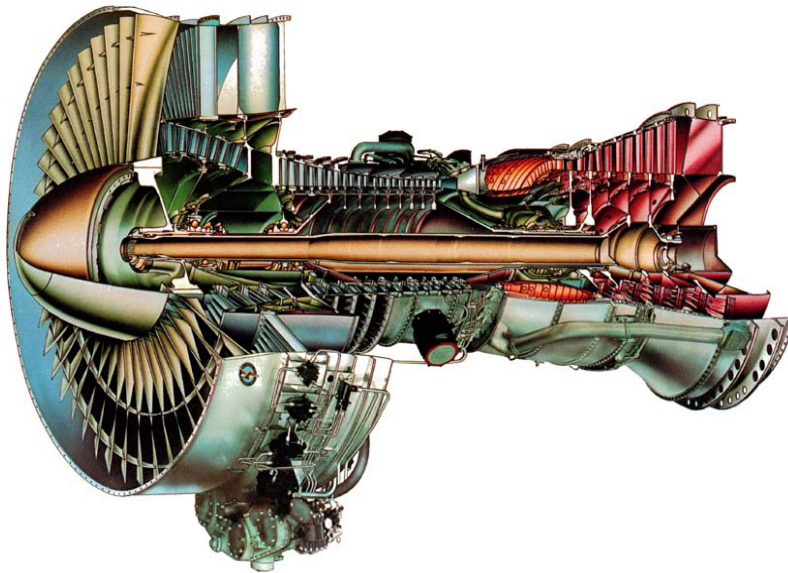


# China Resource Dependencies

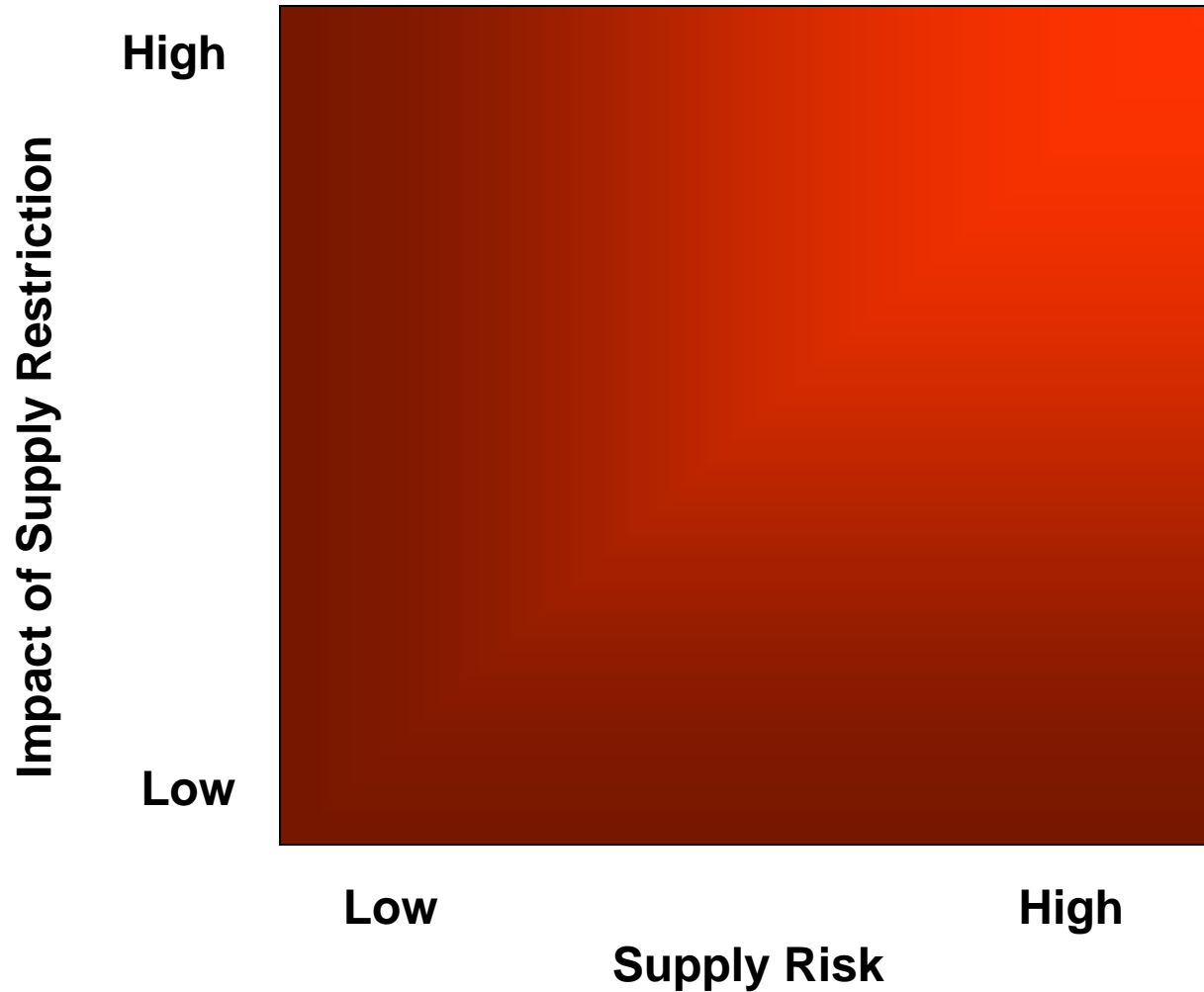


# The Second Dimension of Criticality: Impacts of Supply Restriction

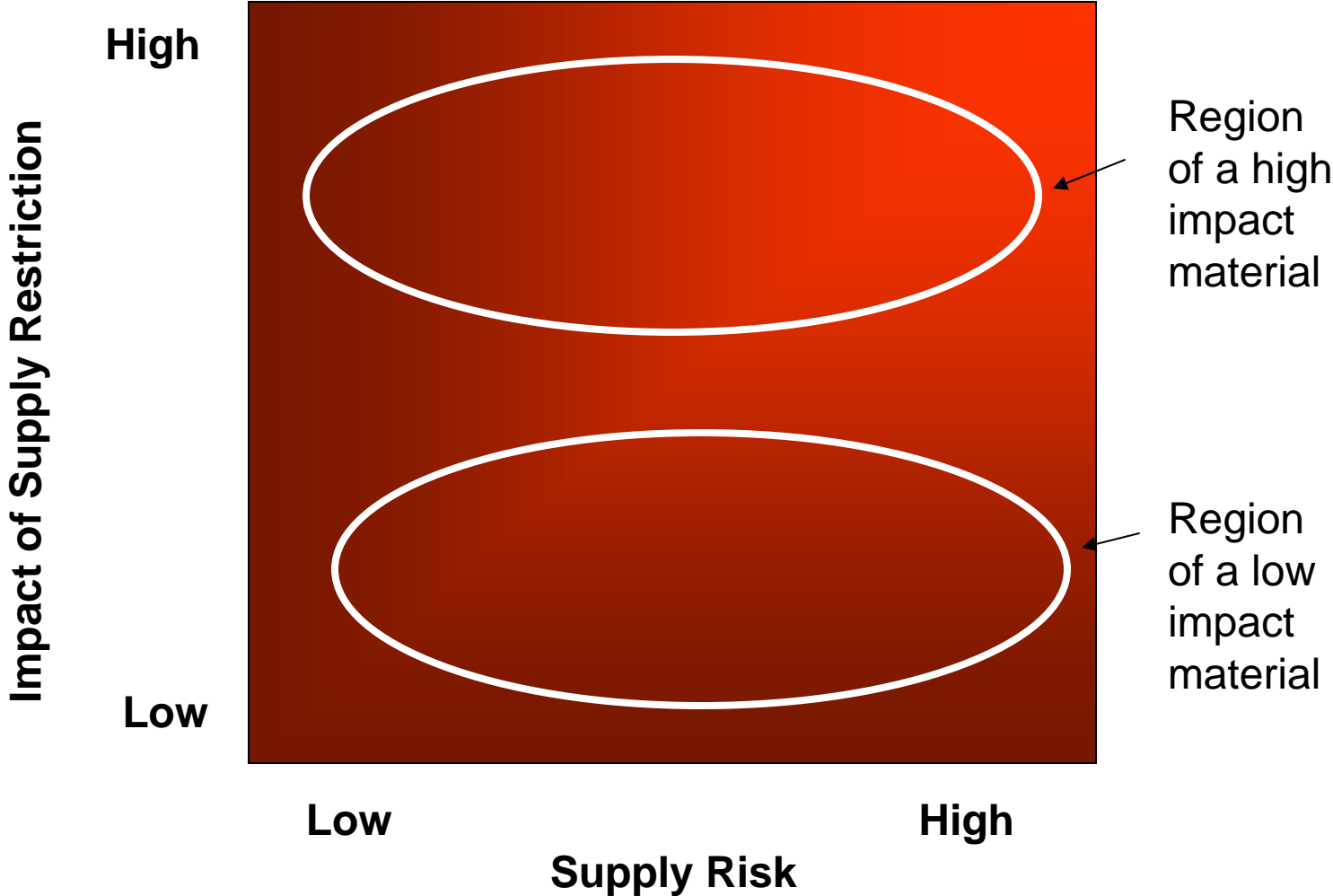
- Prevents manufacture
- Impedes product development
- Influences profitability



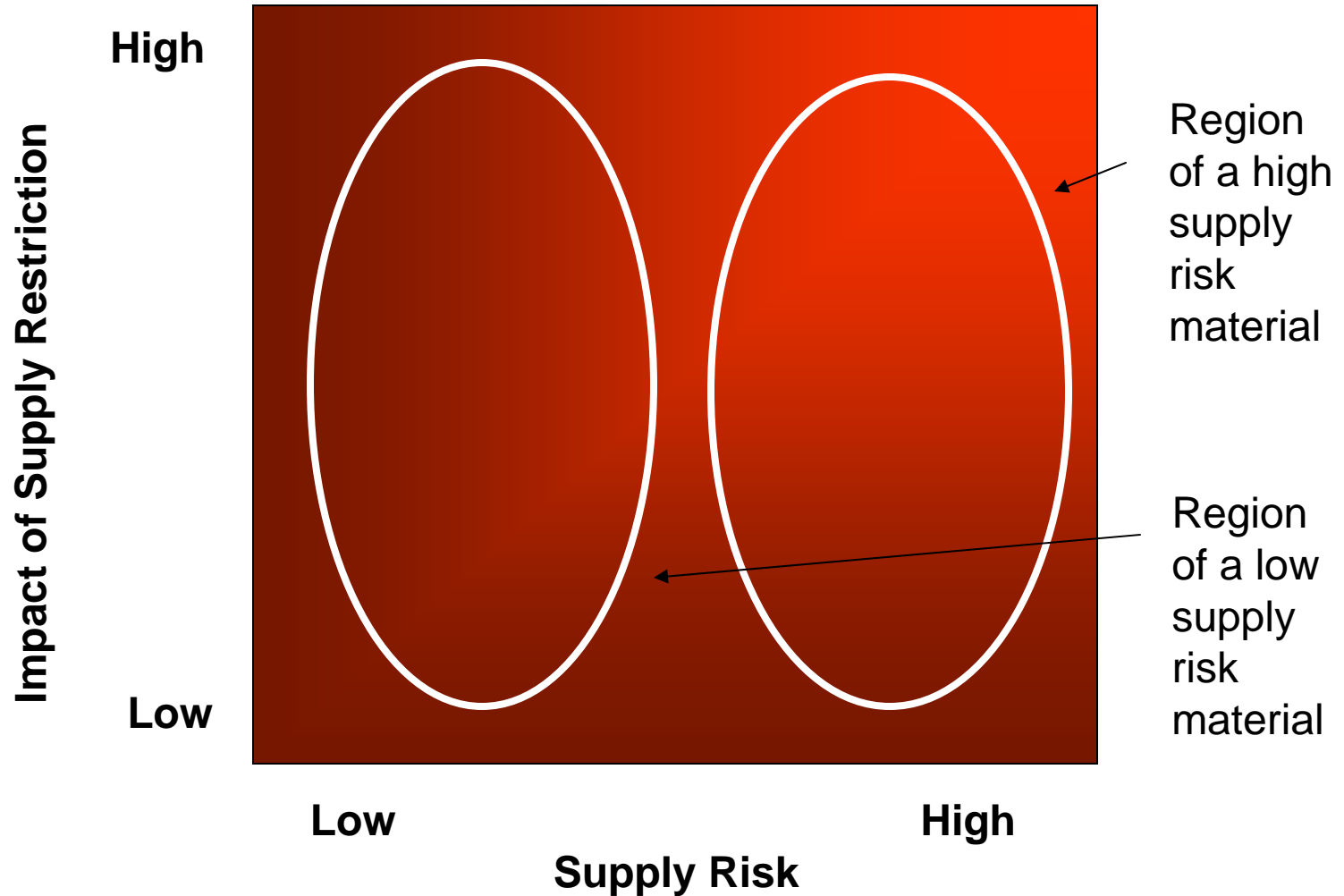
# Two-Dimensional Criticality



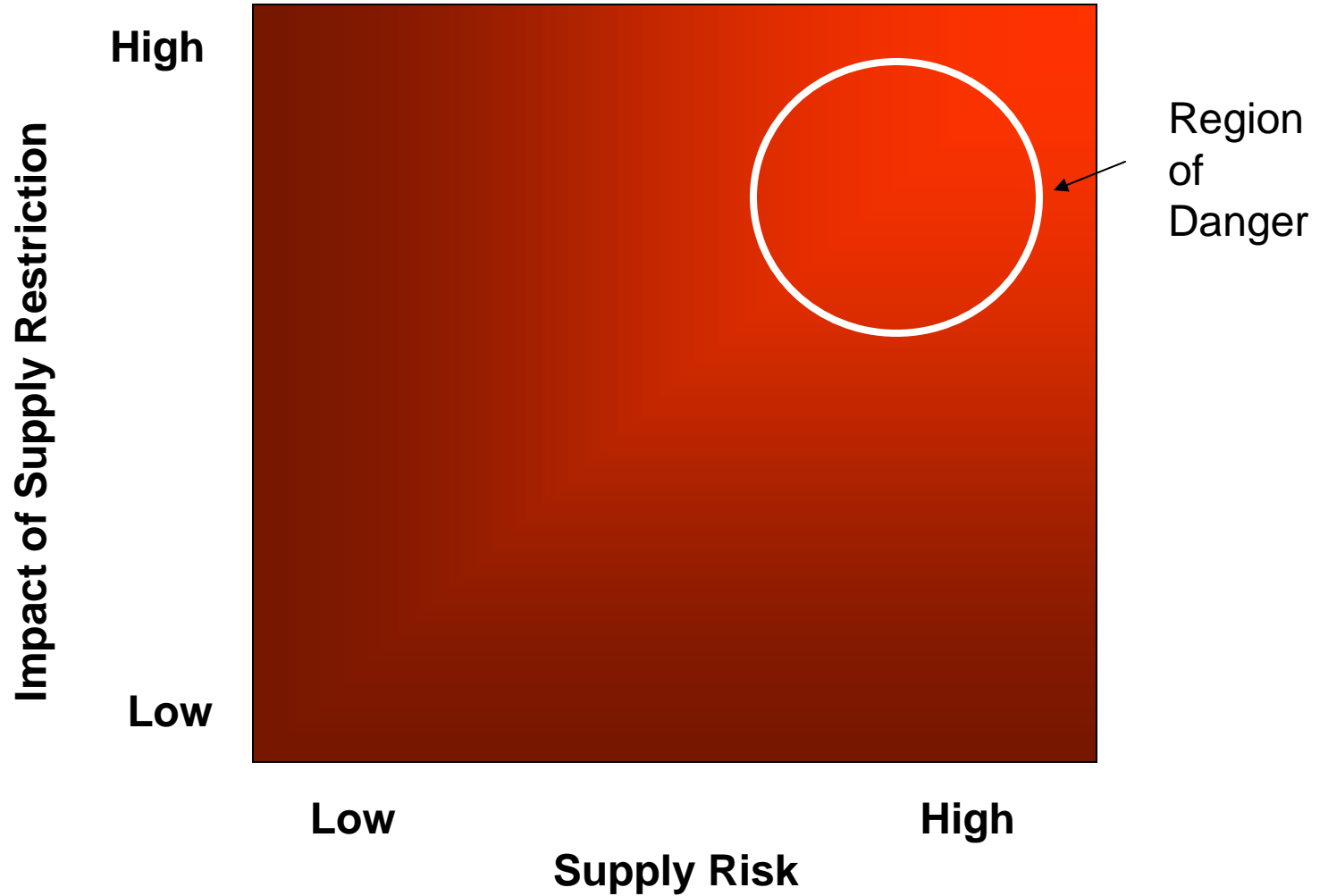
# Locating a Product Material on the “Impact of Restriction” Axis



# Locating a Product Material on the “Supply Risk” Axis



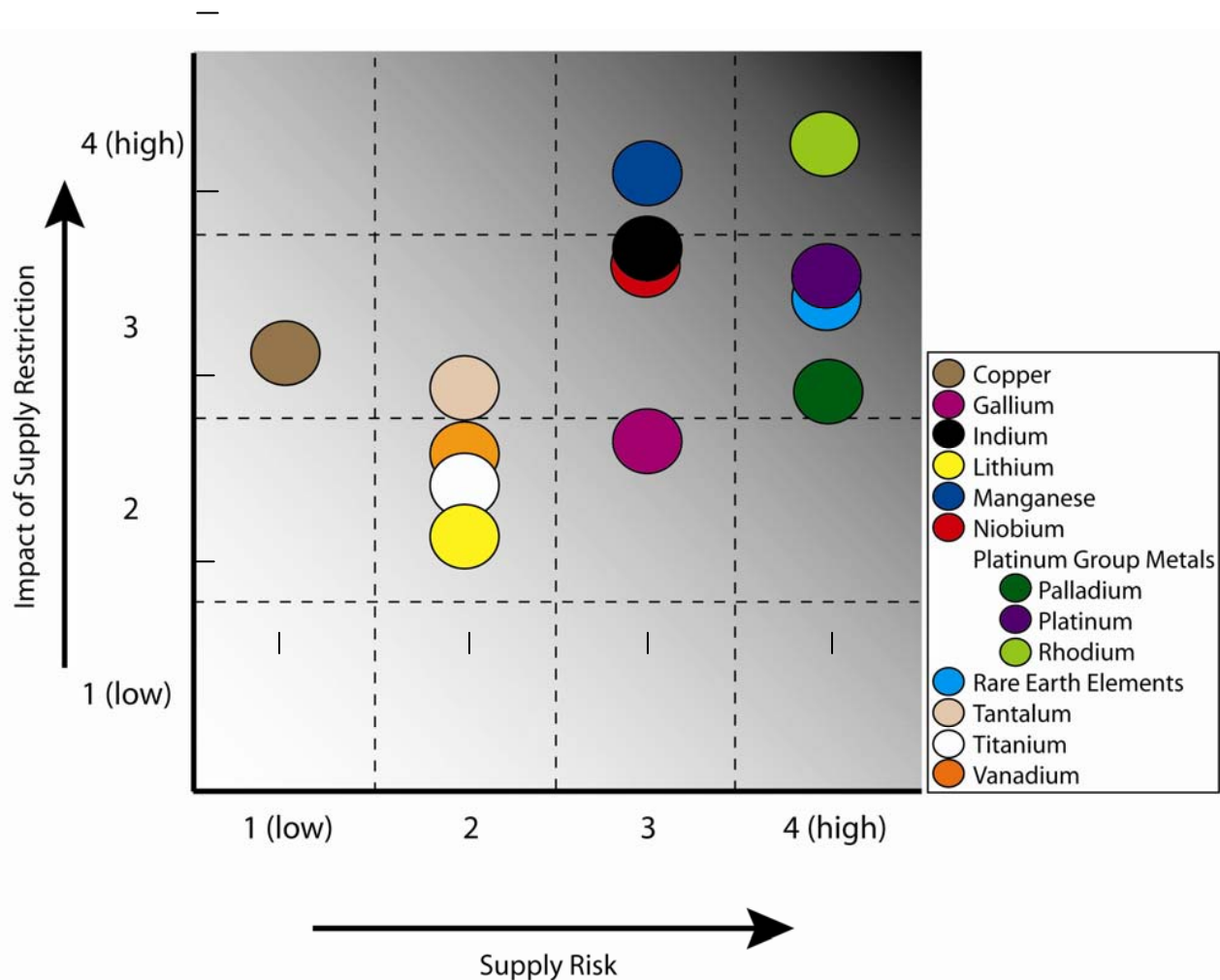
# Identifying the “Region of Danger”



# Criticality Example: Platinum

- Application in the auto industry: CO and HC reduction in catalytic converters
- Substitutes
  - Gasoline catalytic converters: Palladium
  - Diesel catalytic converters - None
- Nature of criticality
  - Primary concern: “No build” condition
  - Secondary concern: Price (\$1200/troy oz on 2/20/07, \$2095/troy oz on 5/9/08)

# Criticality of 11 Minerals Evaluated by the U.S. National Research Council



Substitution as a solution for  
resource depletion – Is this a  
reasonable option?

# Aircraft Engine Combustors

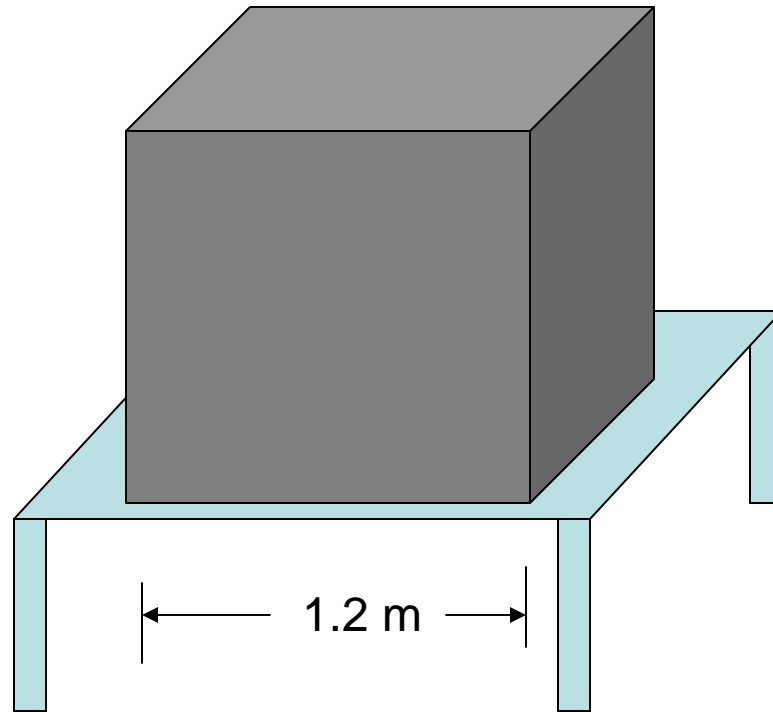


# Aircraft Engine Combustors



Rhenium: Only element whose alloys can withstand modern combustor temperatures

# The World's Annual Production of Rhenium



# Liquid Crystal Display

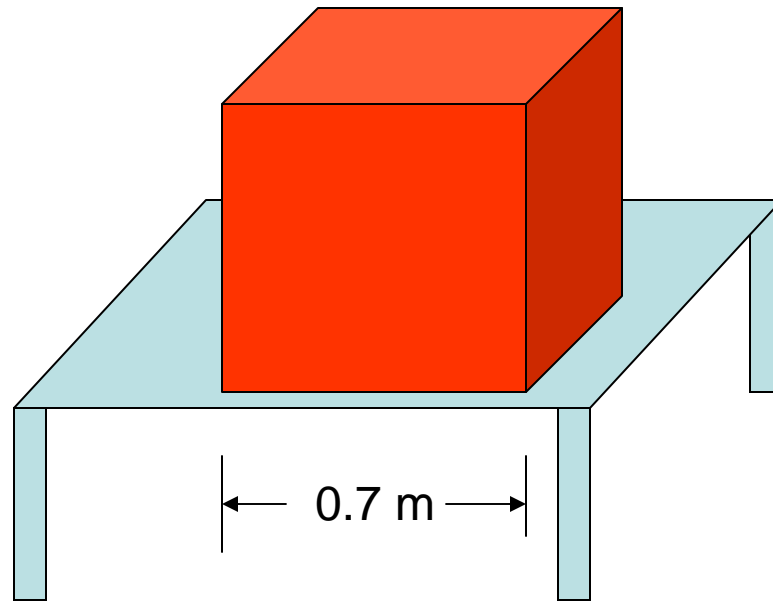


# Liquid Crystal Display Phosphors



Europium: Only element known suitable as LCD red phosphor activator

# The World's Annual Production of Europium



# POTENTIALLY LIMITED RESOURCES

- Resource appears small relative to annual extraction: Au, Cu, Zn, PGMs (Pt, Pd, Rh)
- Resource appears small and most uses are non-substitutable: In, Re, Eu, Hf, Er
- Principal source countries are politically problematic: Co, Ta
- Very large energy requirements: Al, Ti
- Toxicity limited: Pb, Hg, As, Cd

# A Mine of the Past: (Bingham Canyon, AZ Copper Mine)



# A Mine of the Future



# Summary

- Non-renewable resource availability requires a balance between supply and demand
- Modern technology employs most of the periodic table of resources
- We lack sufficient data, but limits to non-renewable resources are quite possible in the next decade or two
- As we deplete ore in the ground, our cities are becoming the mines of the future. We need to learn how to be better urban miners

# Crude Steel Production in China and India, 1945-2005

