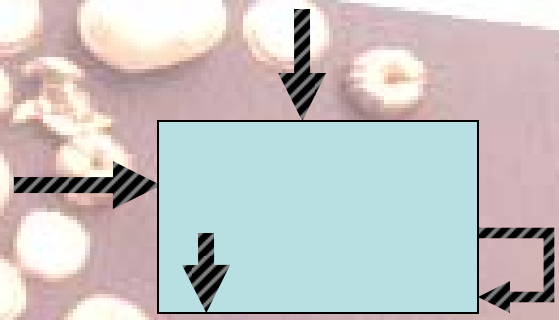
Center for Industrial Ecology

Yale School of Forestry & Environmental Studies

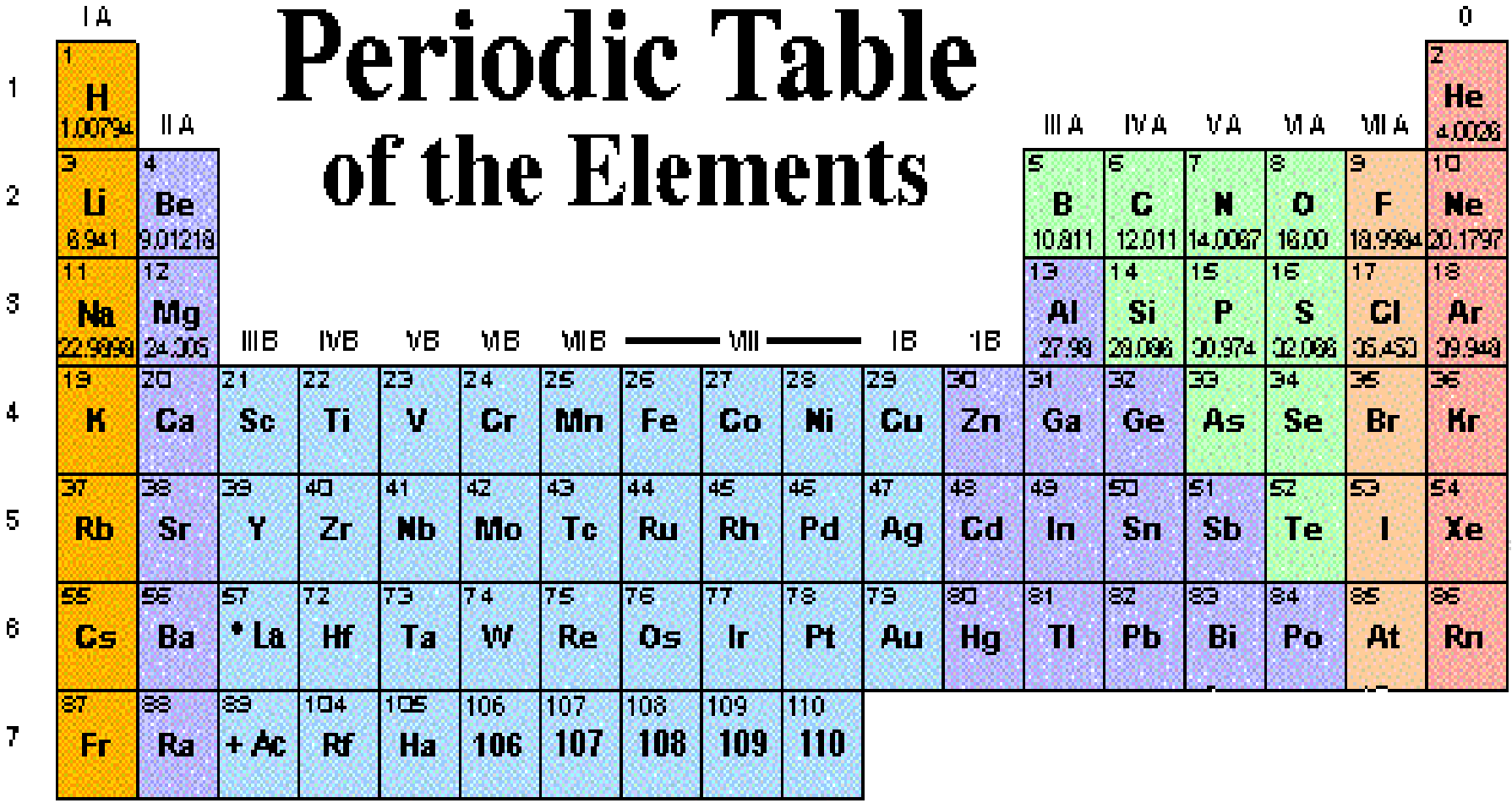
The Criticality of Materials

Thomas E. Graedel

Yale University

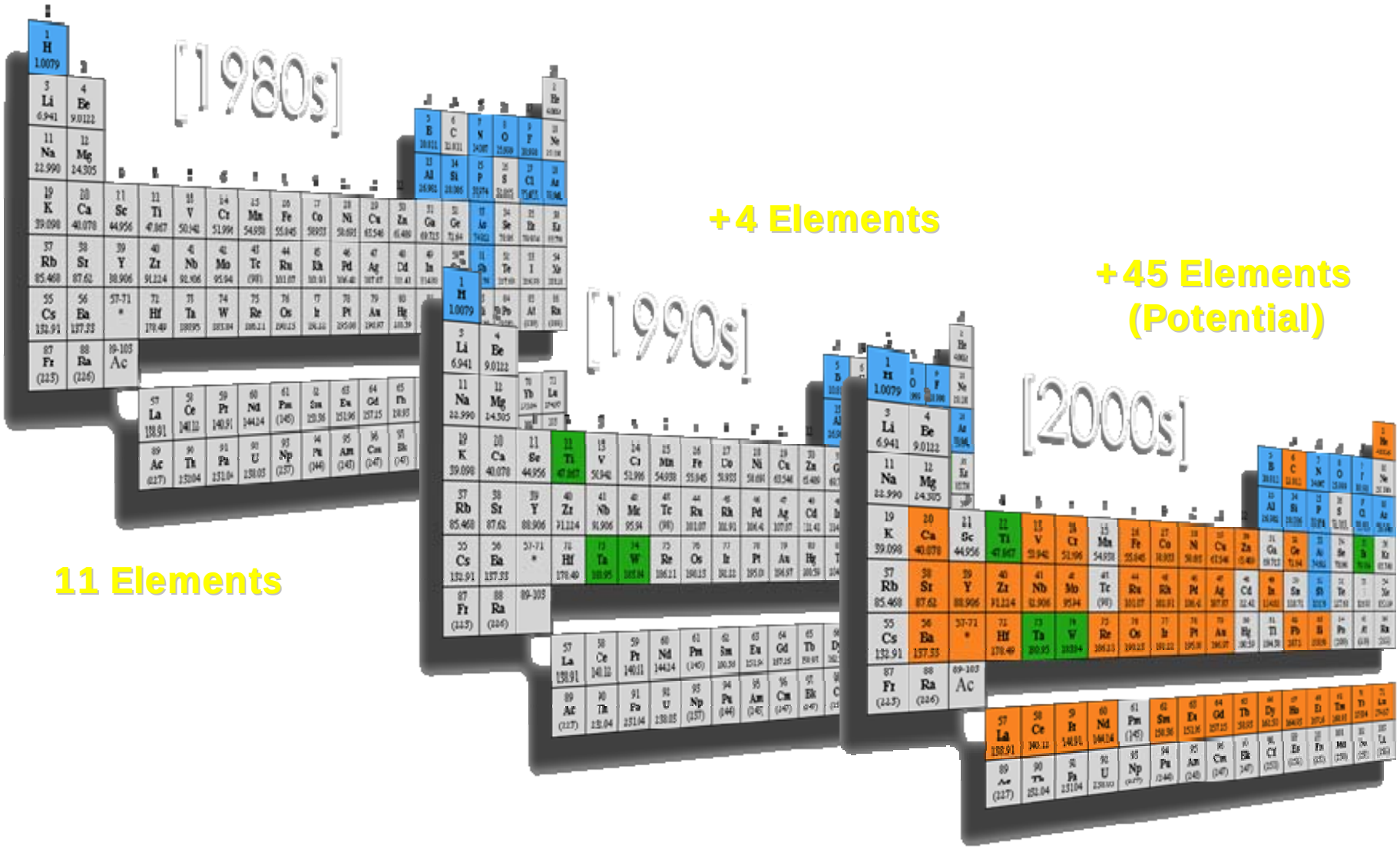


Periodic Table of the Elements



* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

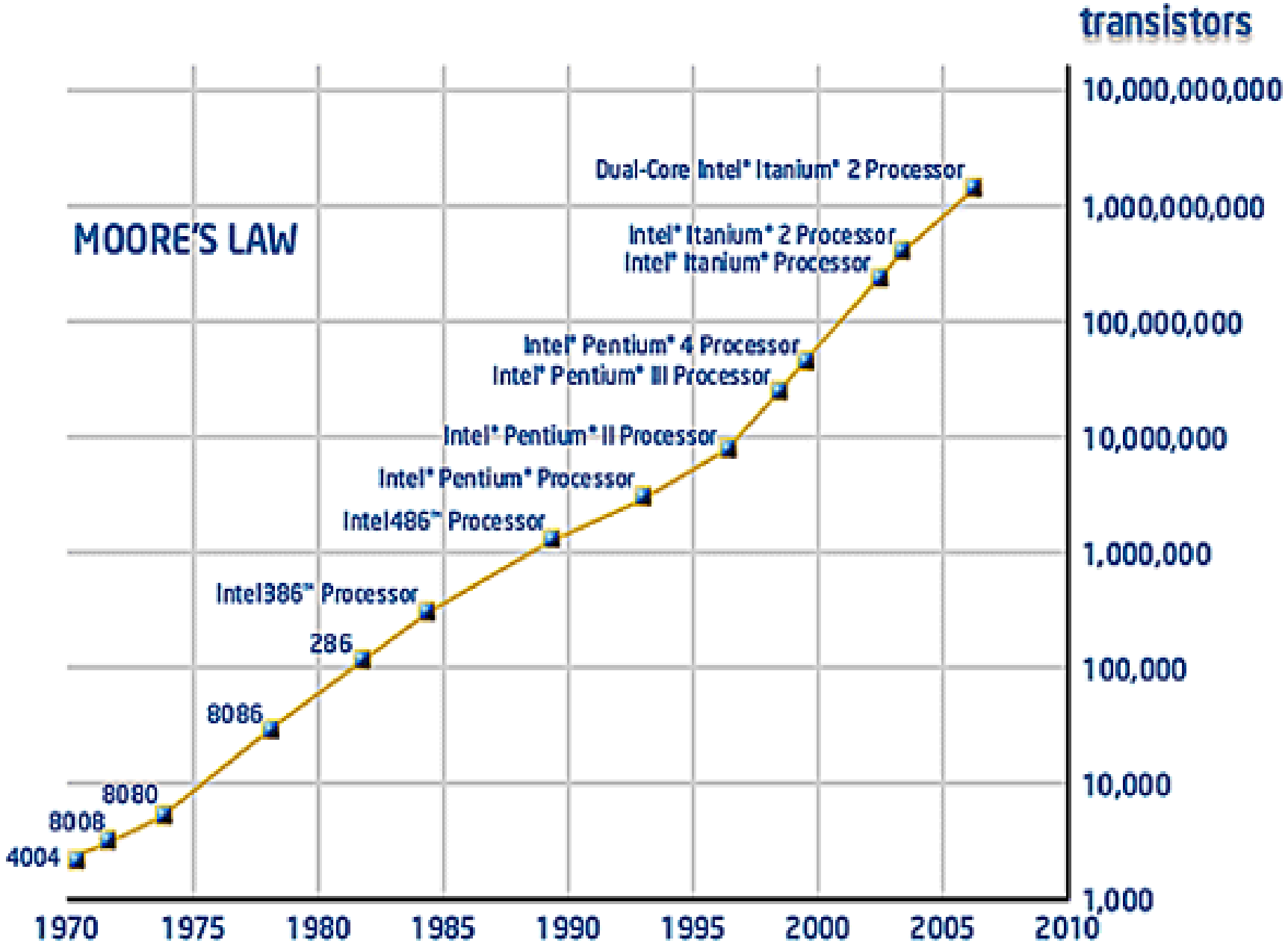
Metal Linkages in the New Mineralogy

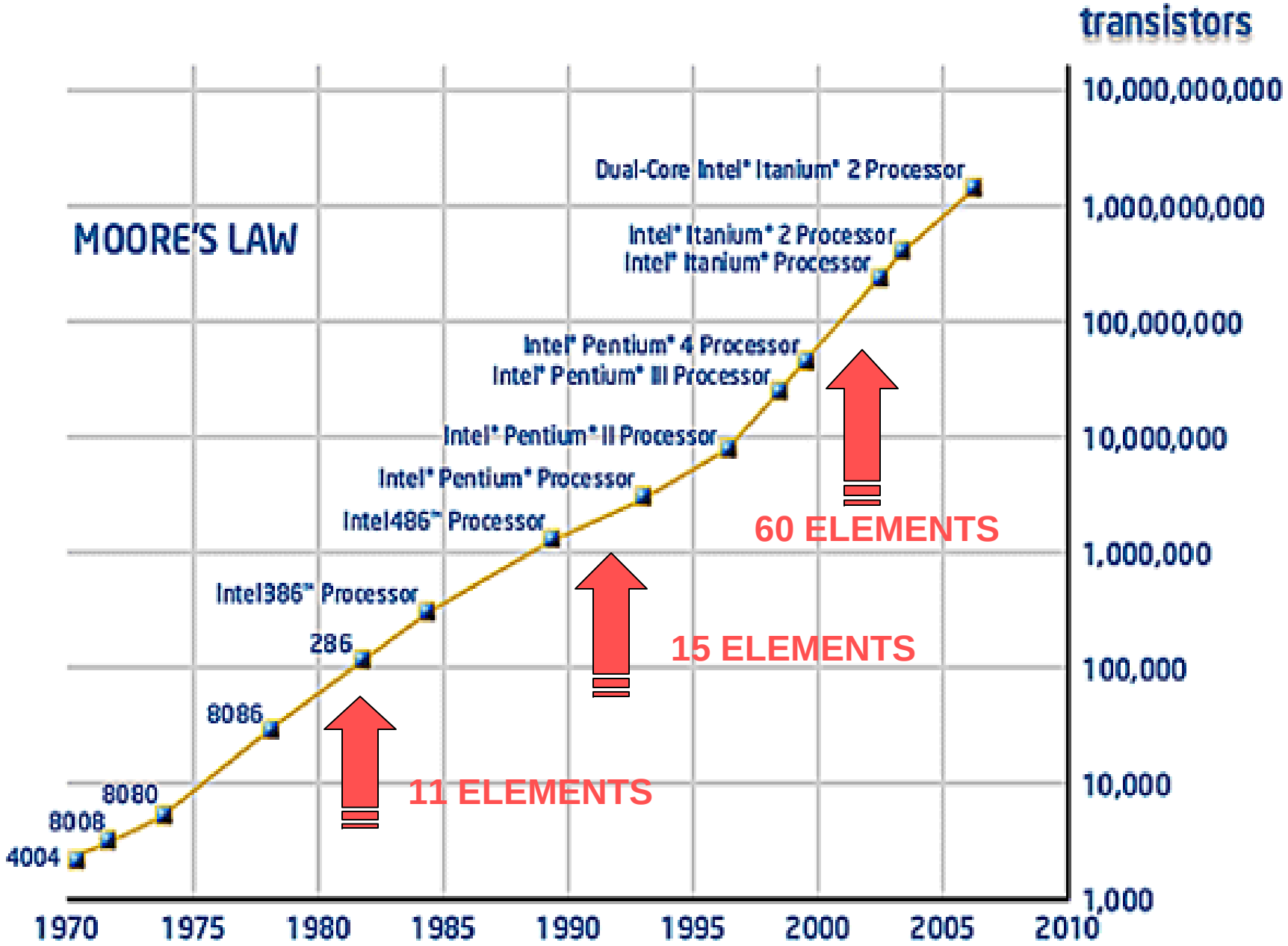


Source: T. McManus, Intel Corp., 2006

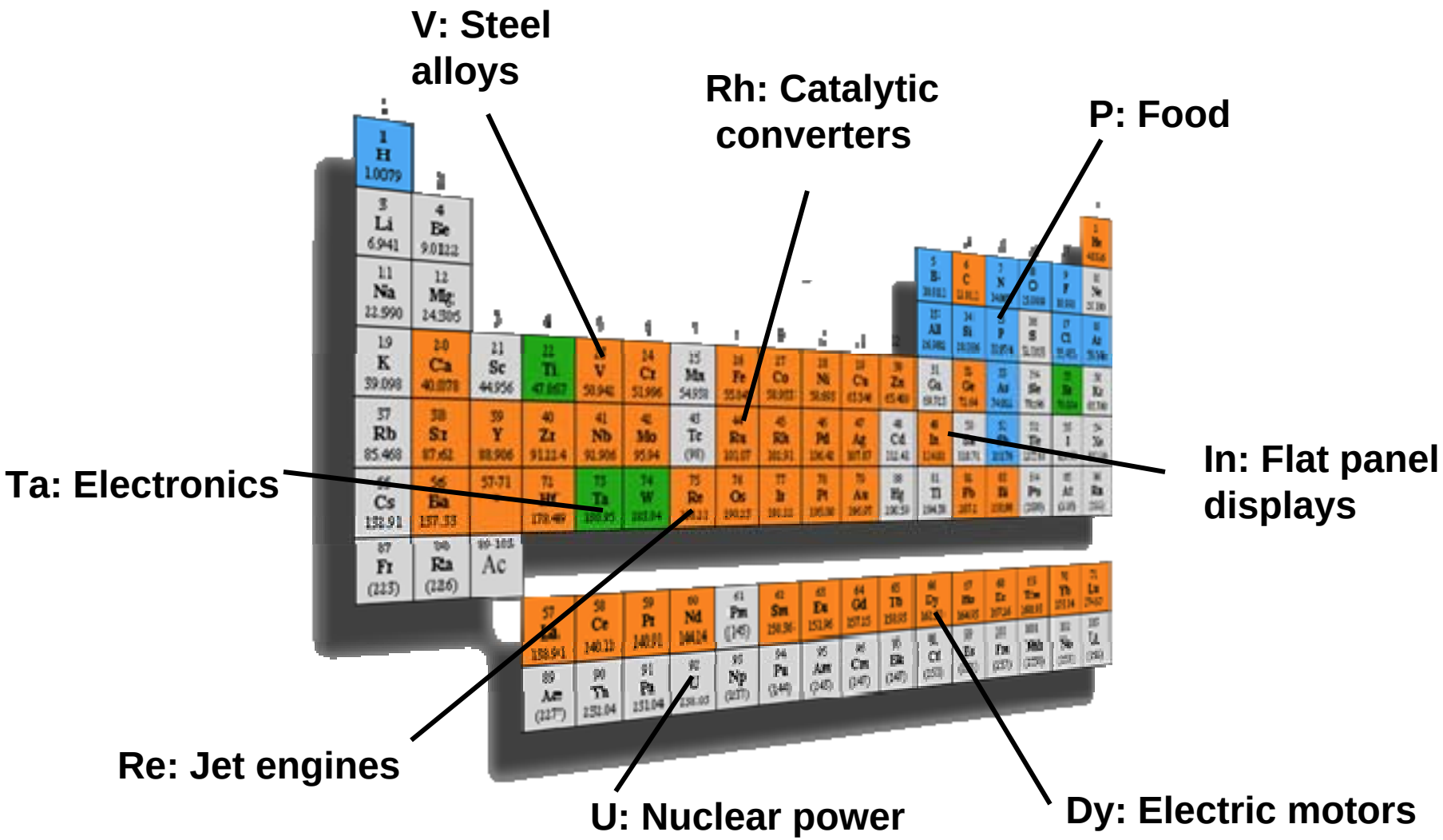
Elemental Functions in Electronics

- Germanium – semiconductors
- Copper – circuit connections
- Tantalum – capacitor
- Antimony – diodes
- Yttrium – red phosphor
- Indium – transistors
- Terbium – green phosphor activator
- Hafnium – transistor insulator


transistors
MOORE'S LAW
Dual-Core Intel® Itanium® 2 Processor
Intel® Itanium® 2 Processor
Intel® Itanium® Processor
Intel® Pentium® 4 Processor
Intel® Pentium® III Processor
Intel® Pentium® II Processor
Intel® Pentium® Processor
Intel486™ Processor
Intel386™ Processor
286
8086
8080
8008
4004
10,000,000,000
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
1970
1975
1980
1985
1990
1995
2000
2005
2010

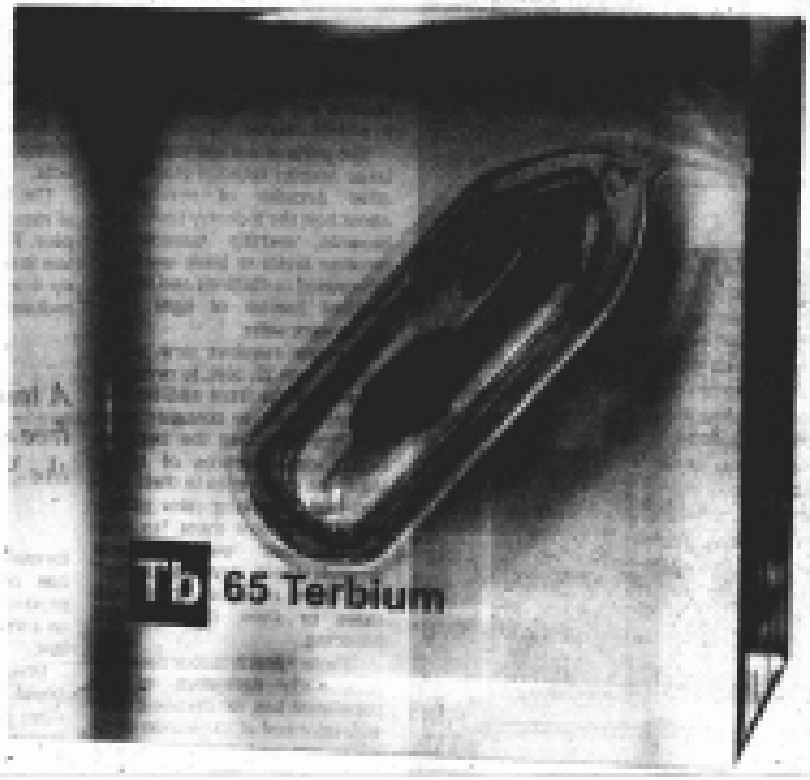

transistors
MOORE'S LAW
10,000,000,000
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
Dual-Core Intel® Itanium® 2 Processor
Intel® Itanium® 2 Processor
Intel® Itanium® Processor
Intel® Pentium® 4 Processor
Intel® Pentium® III Processor
Intel® Pentium® II Processor
Intel® Pentium® Processor
Intel486™ Processor
Intel386™ Processor
286
8086
8080
8008
4004
60 ELEMENTS
15 ELEMENTS
11 ELEMENTS
1970
1975
1980
1985
1990
1995
2000
2005
2010

The No-Build” Periodic Table

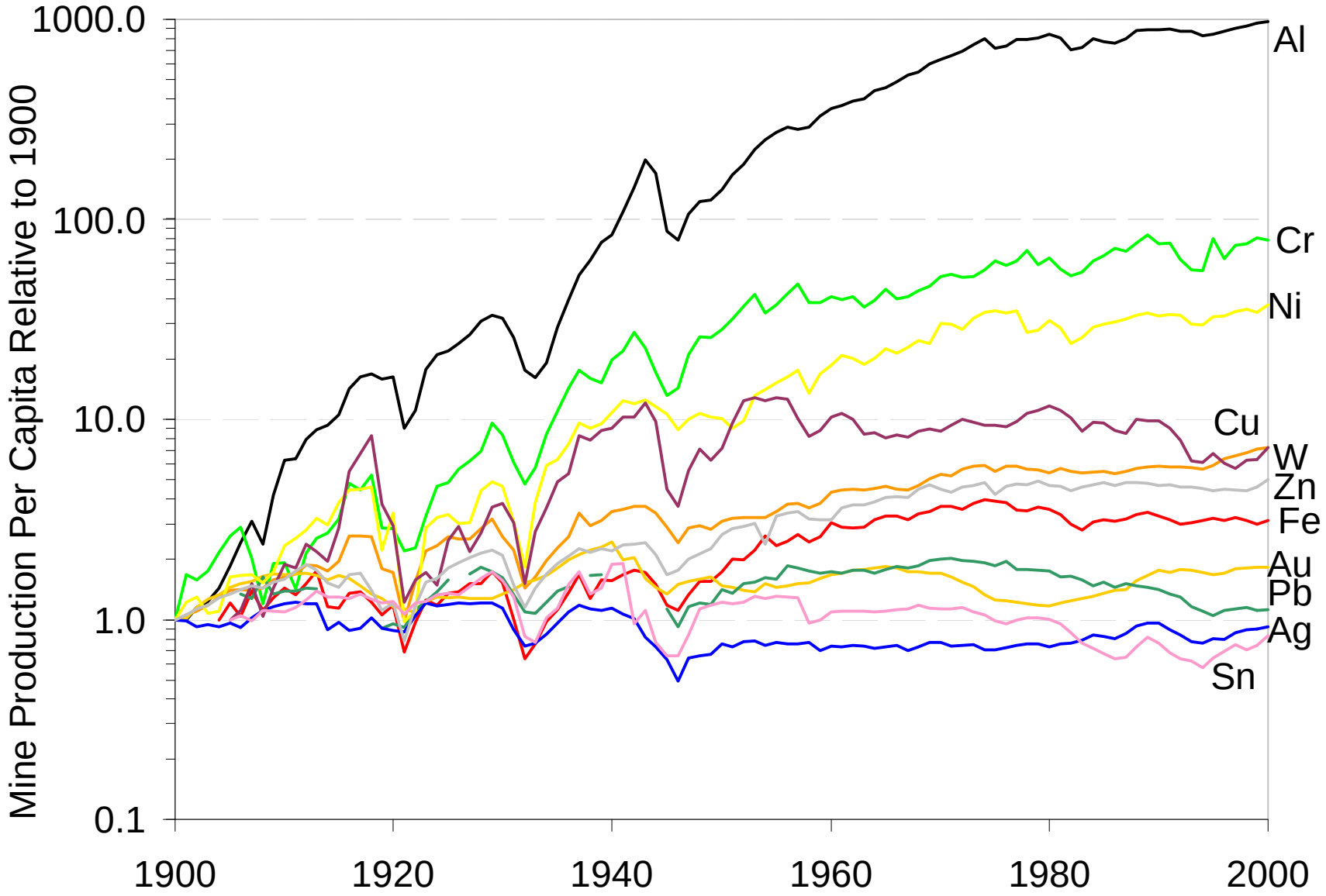


Business Day
The New York Times
TUESDAY, SEPTEMBER 1, 2009

China Tightens Grip On Rare Minerals

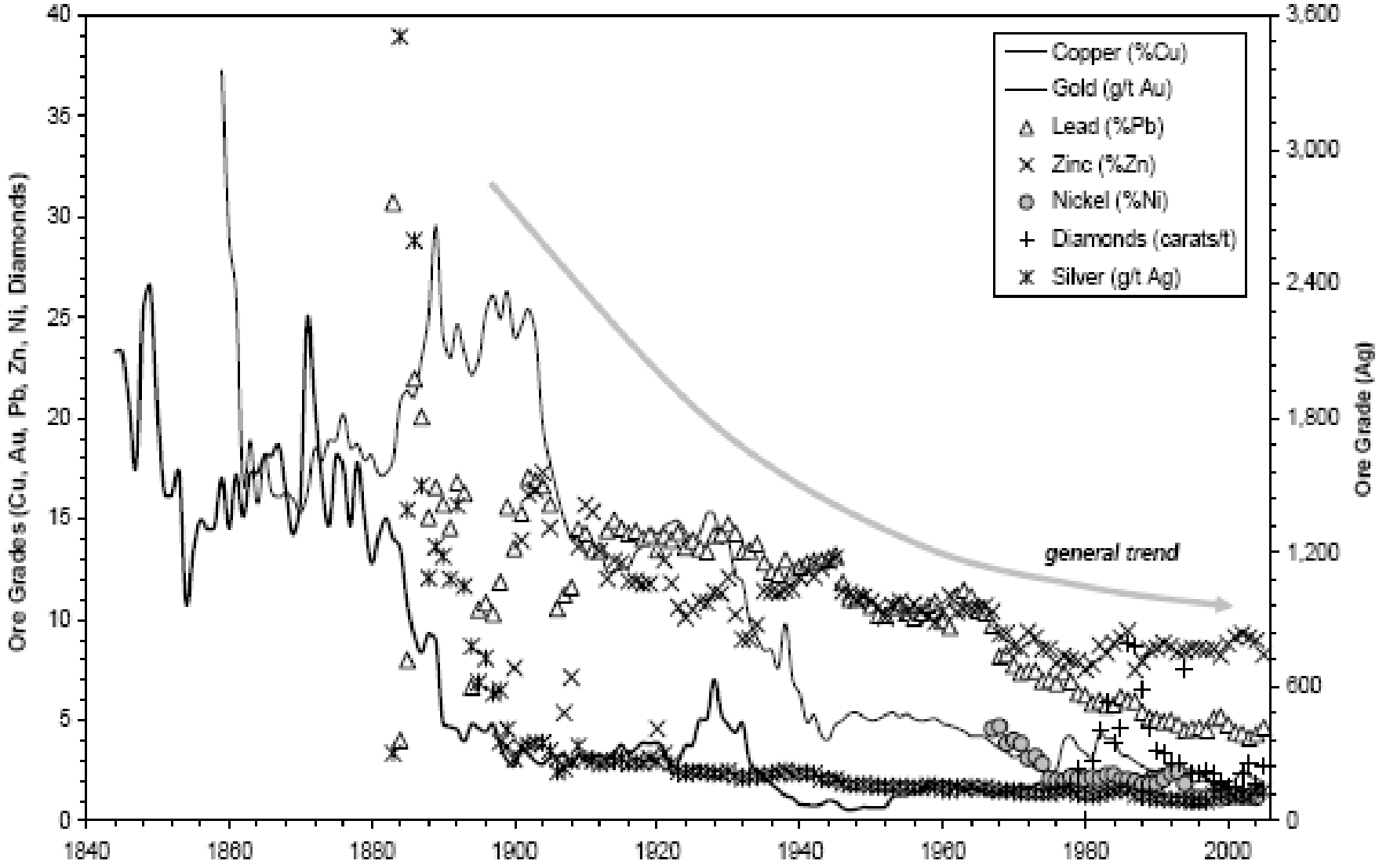


Global per Capita Metals Use in the 20th Century

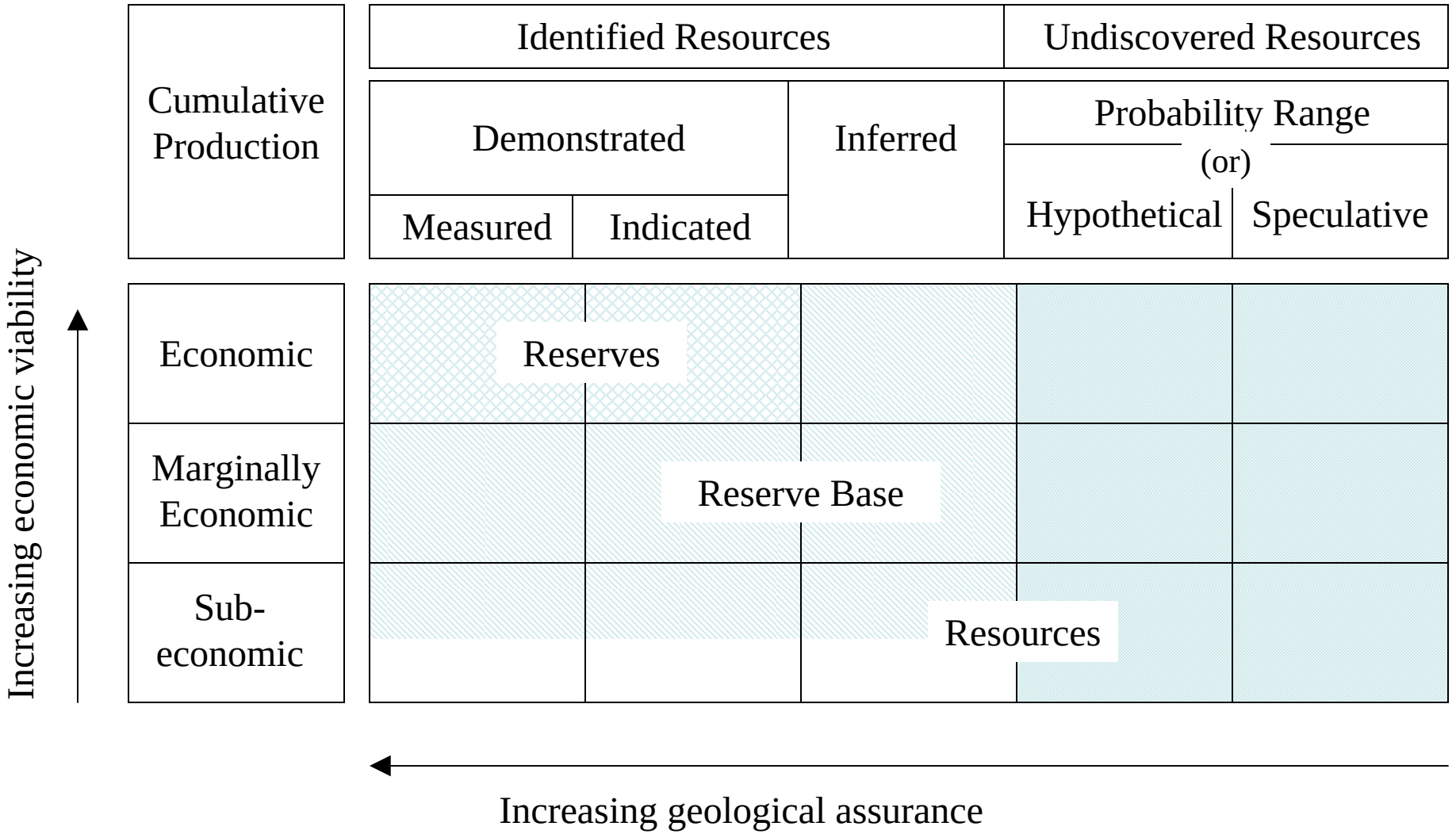


Histories of Australian Ore Grades, 1845-2007

Source: G.M. Mudd, Sustainability of Mining in Australia, Research Report No. RR5, Monash Univ., 2007.



The McKelvey Diagram



Why Don’t We Get Metals From Recycling?

Brake Linings: An Example of Dissipative Use

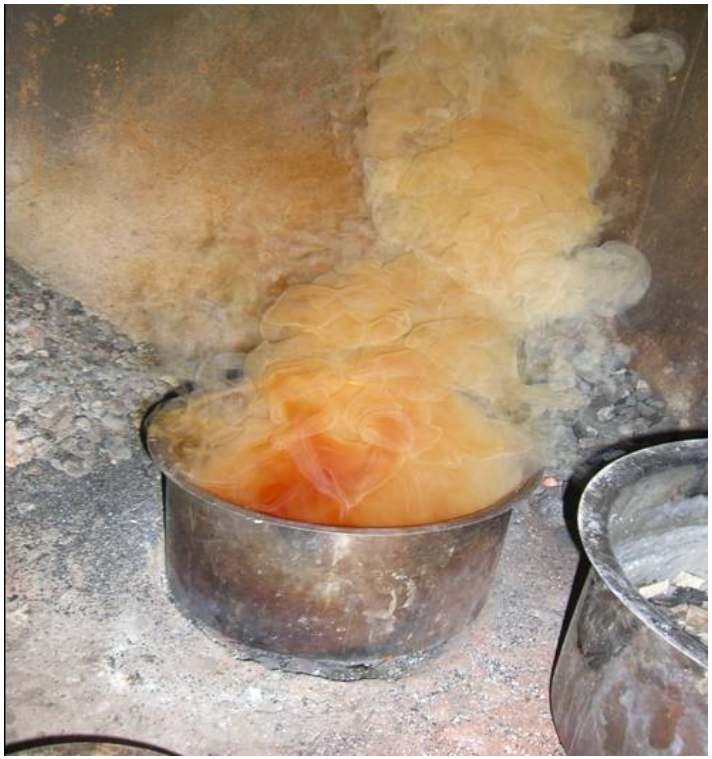
Brake linings contain phenolic resin binder, clay and powder fillers, graphite lubricants, and metallic fibers (Ba, Ca, Ti, Cu, Mg, Cr, Sb, Zn, Zr)

Image courtesy of Sansin Brake Co., etrade.daegu.go.kr/.../Brake_Lining.html

Electronics in the Trash:
An Example of Fragmentary Collection

Courtesy of Gothamist.LLC, gothamist.com/2008/02/16/electronics_rec.php

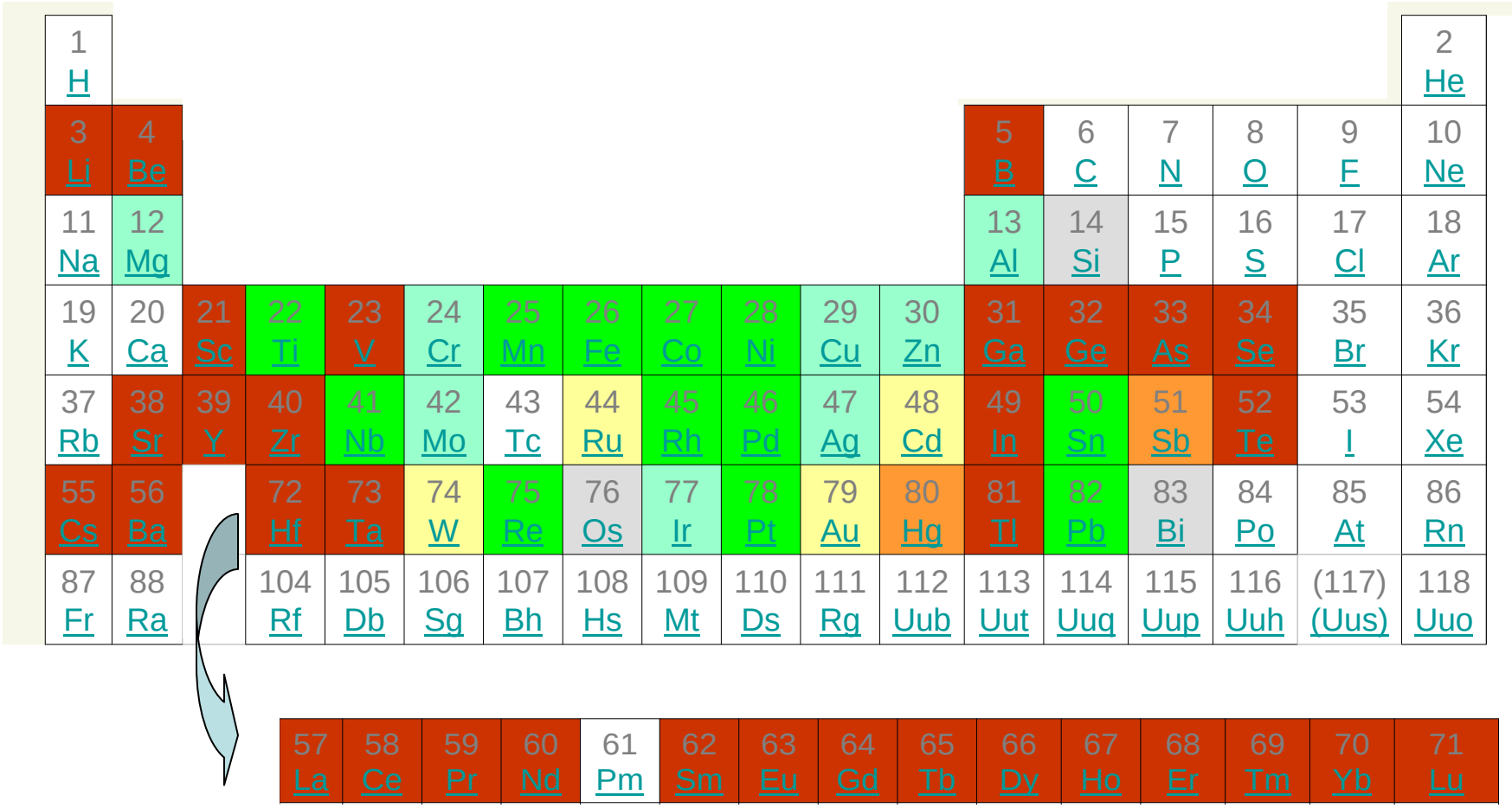
Processing Failures:
Electronic Waste Recycling in India



Courtesy of D. Rochat, EMPA, Switzerland

End of Life Recycling Rate (Global) for Sixty-Two Metals

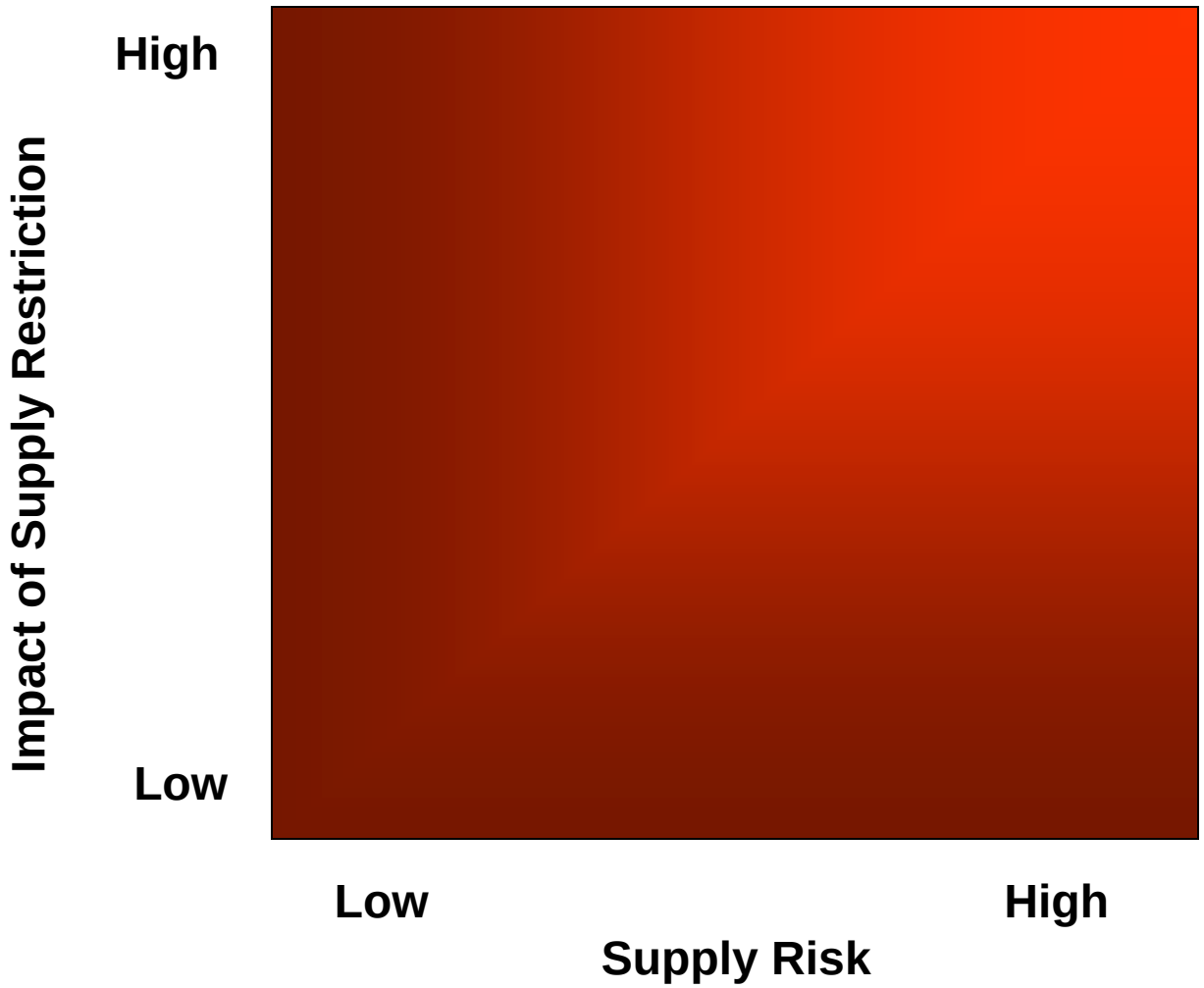
Preliminary as of October 7, 2009



>50% >25-50% >10-25% 1-10% <1% ???

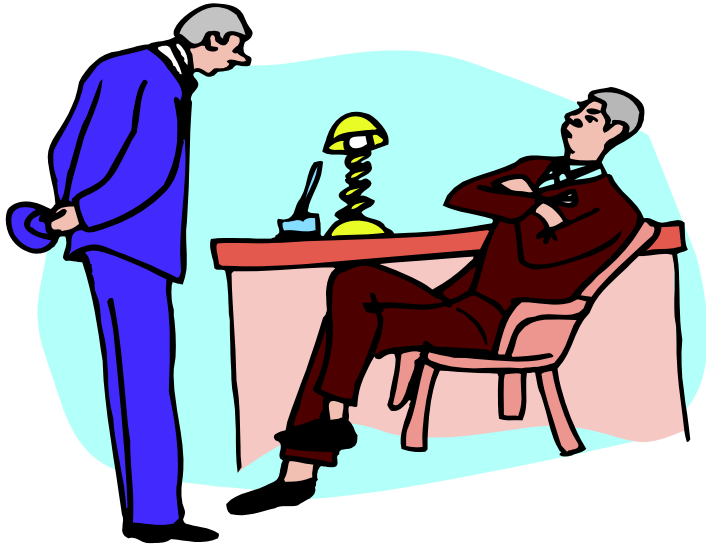
The U.S. National Academy of Sciences 2007 Study of Resource Sustainability

Determining a Material's Criticality



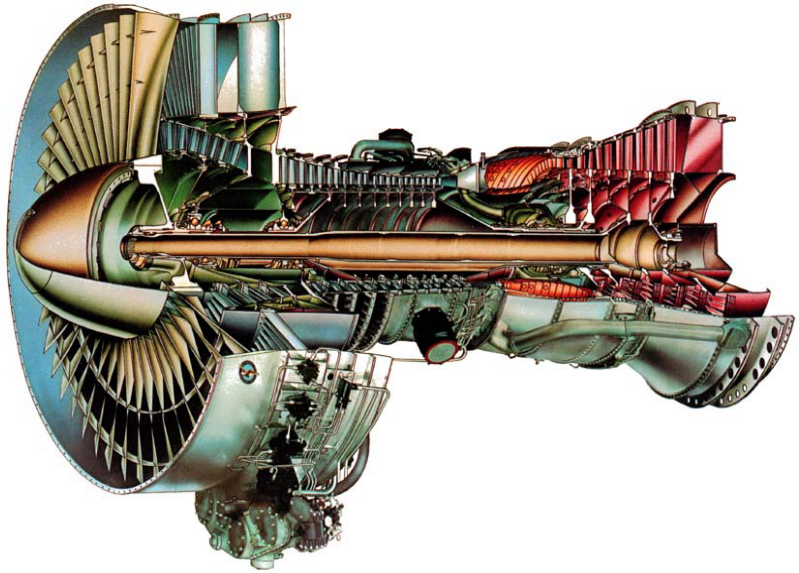
The First Dimension of Criticality
Supply risk

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

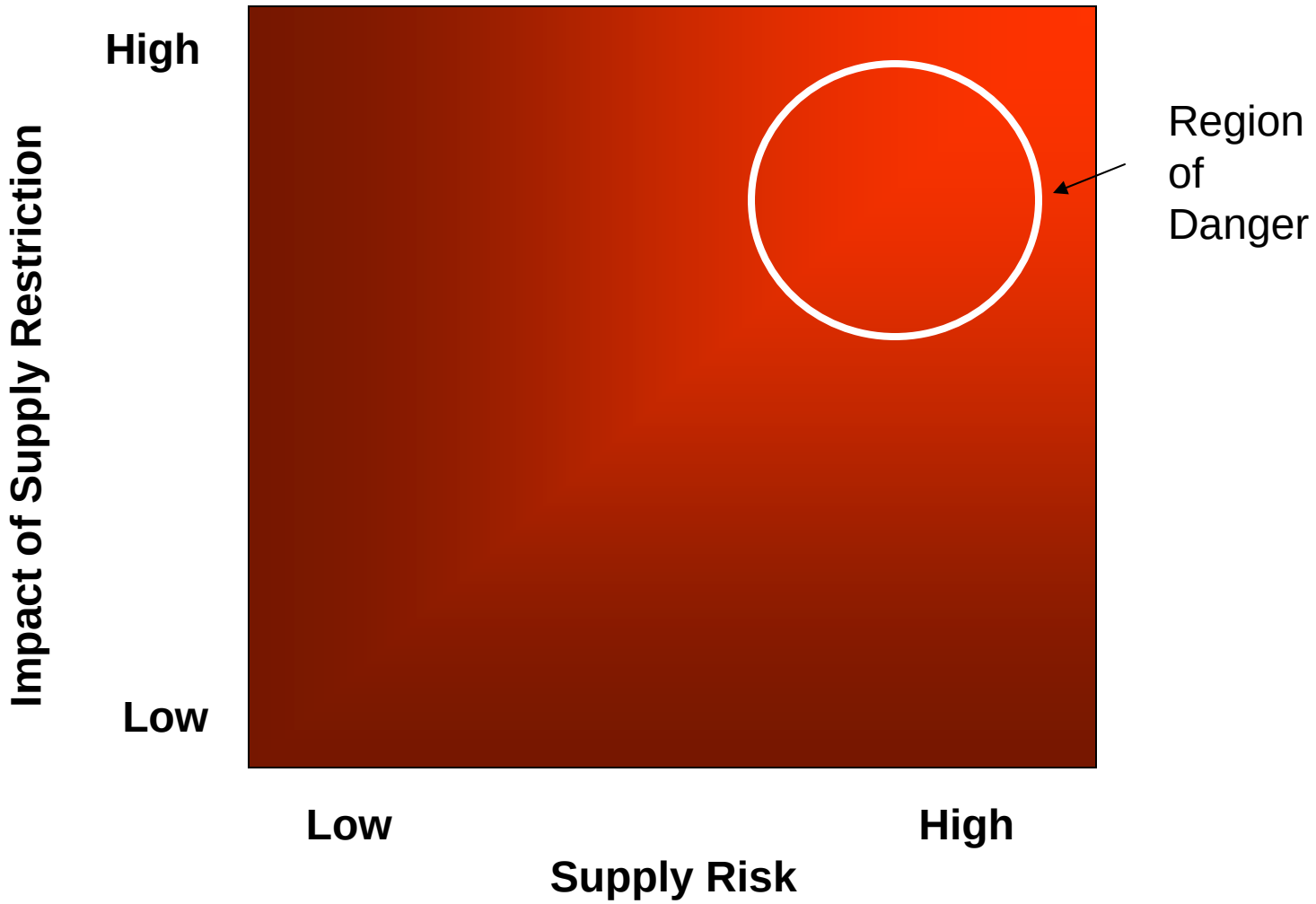


The Second Dimension of Criticality: Impacts of Supply Restriction

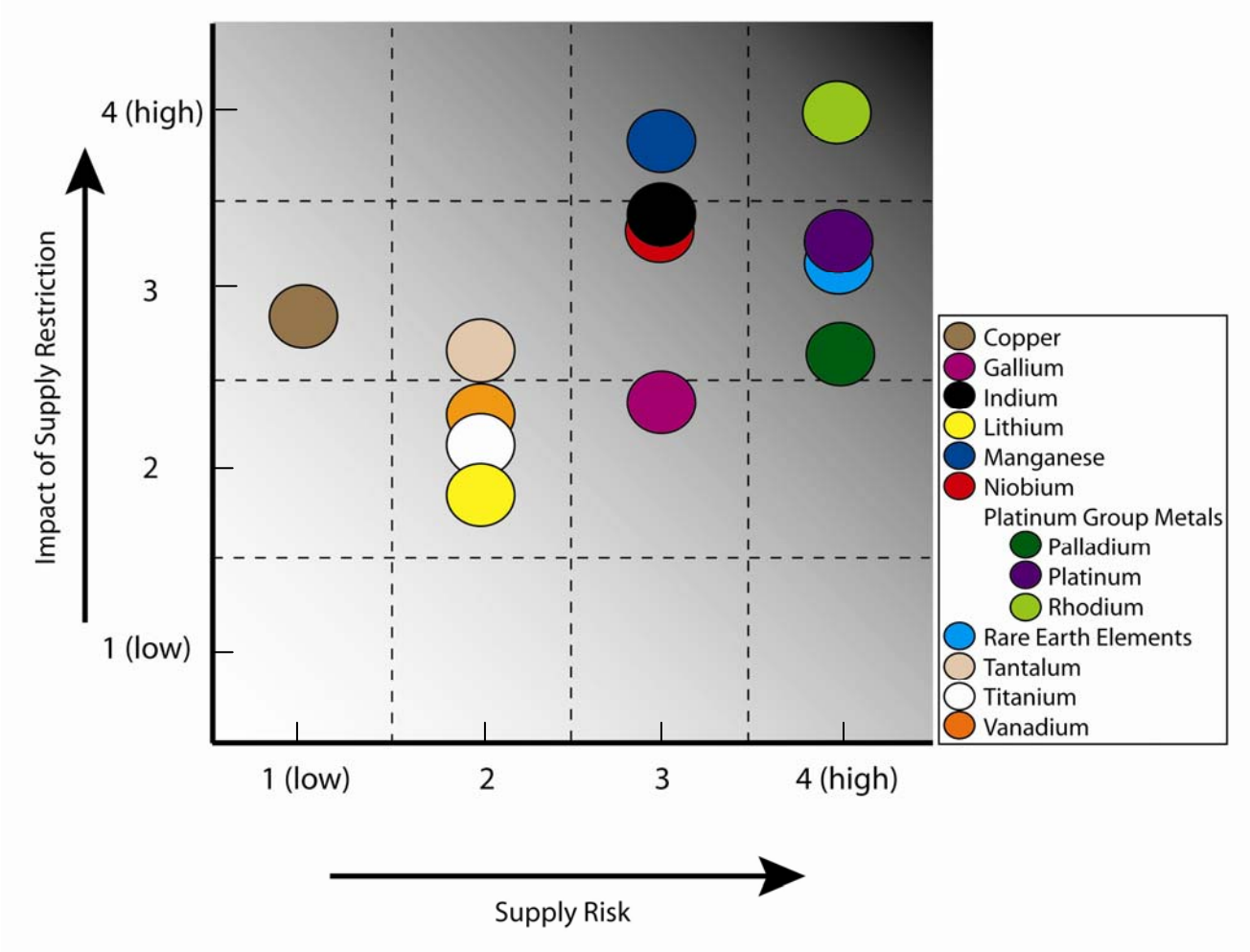
- **Prevents manufacture**
- **Impedes product development**
- **Influences profitability**



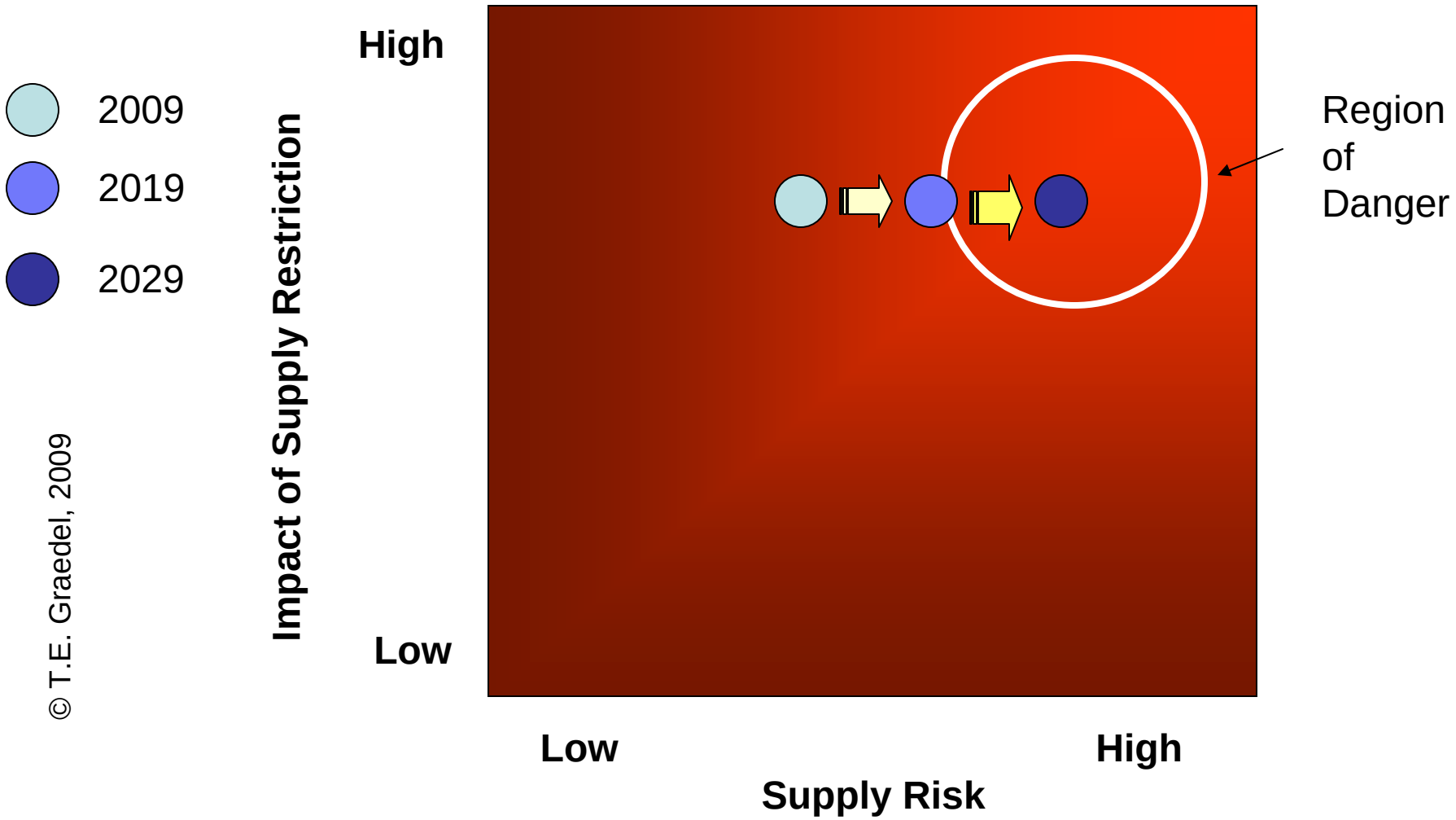
Identifying the “Region of Danger”



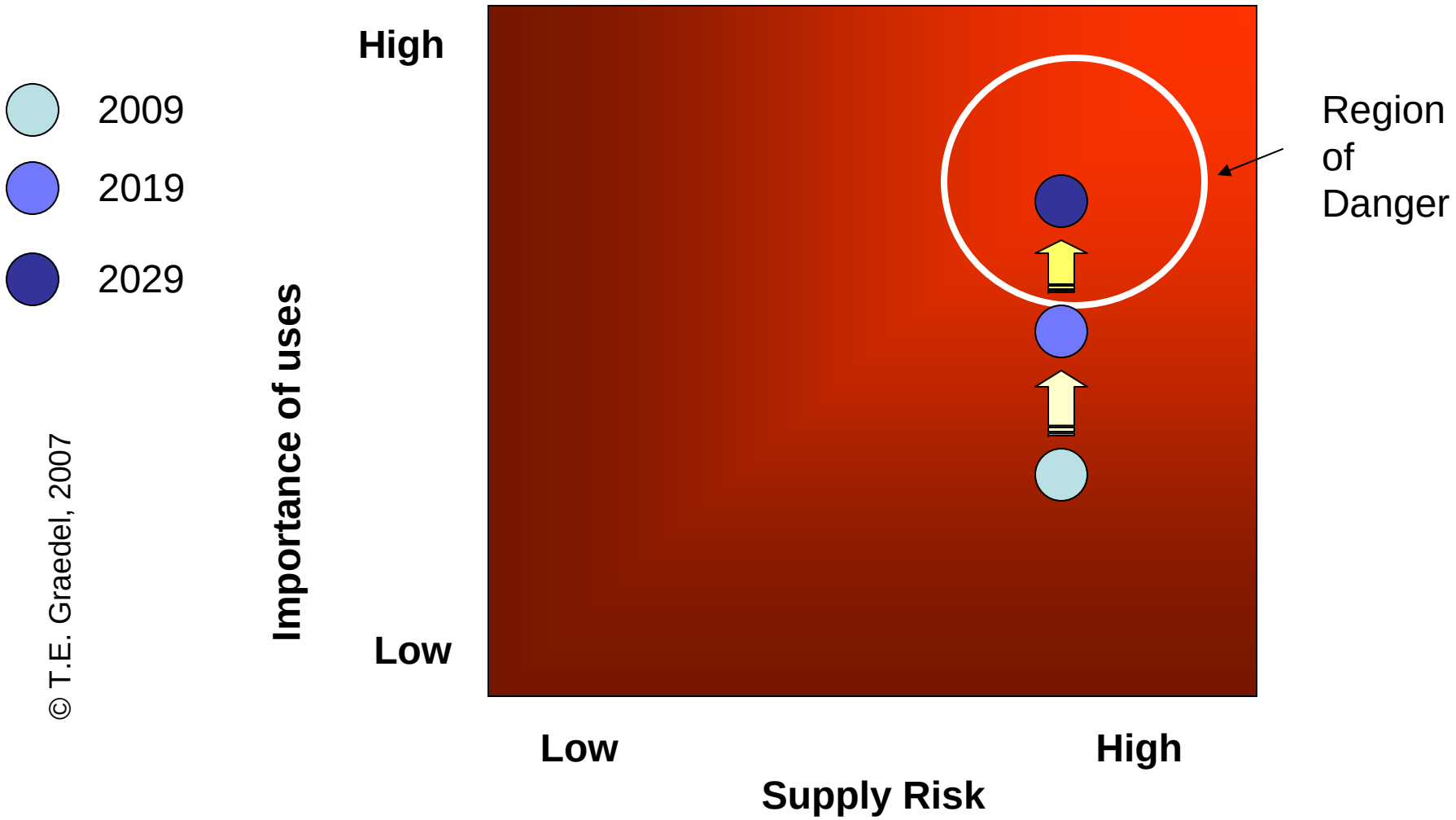
11 Minerals Evaluated



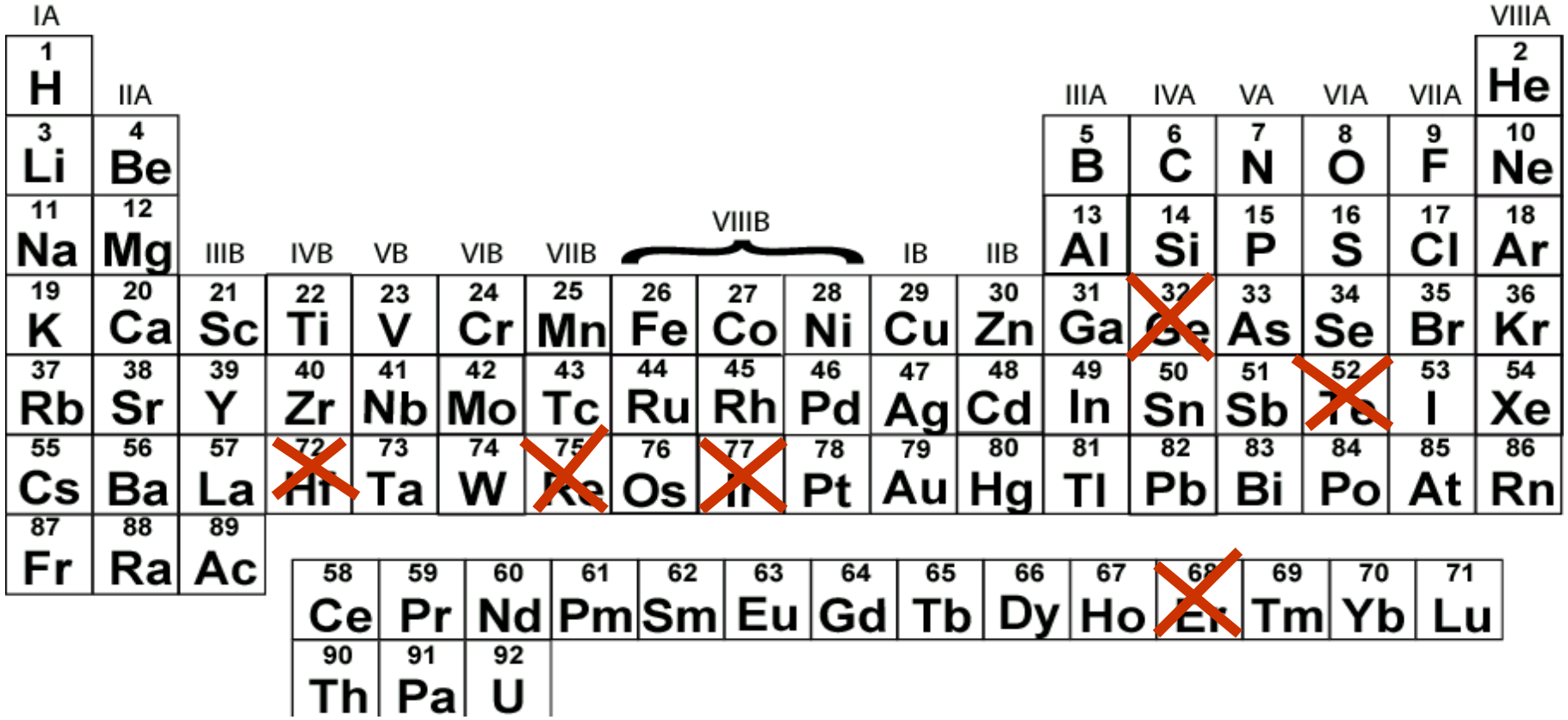
A Possible Major New Supply Risk Scenario



A Possible Major New Use Scenario



Tomorrow's Periodic Table?

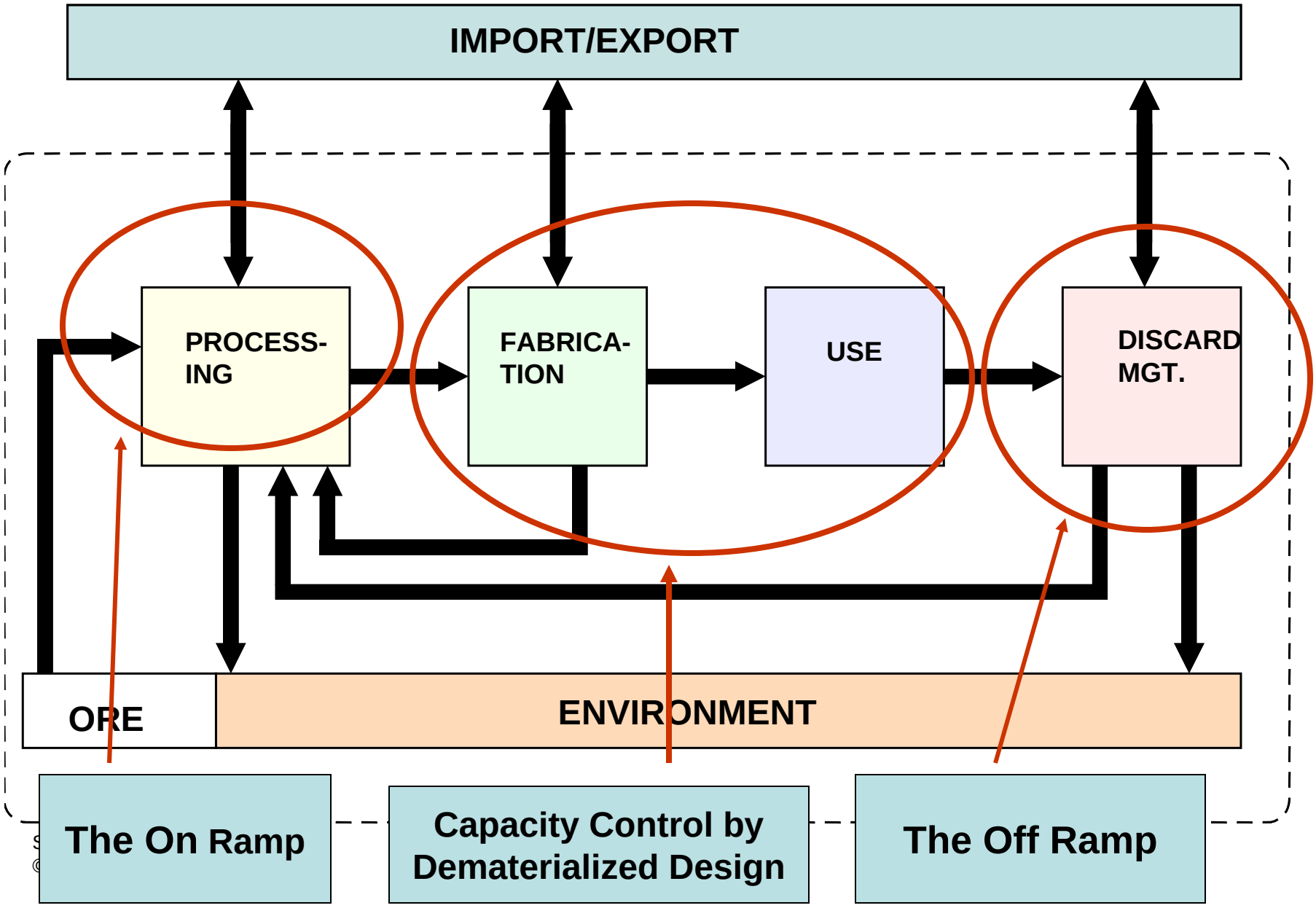


The On Ramp

Capacity control (commuter buses, etc.)

The Off Ramp

Enabling Materials Use and Reuse



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

A Mine of the Future

Summary

- The industrial sector uses essentially all of the periodic table
- Elemental choices that appear (at least in the short to medium term) to be unsubstitutable are increasingly used in modern technology
- Criticality research is now underway, but rather late and beset by significant data challenges
- Long-term prospects for much of the periodic table are quite poorly characterized