

The Past Paves the Way for Future Innovation?

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Sources:

Cummings, Jim, "Remediation-Then, Now and Later... 'You've Come A Long Way Baby" (2022)

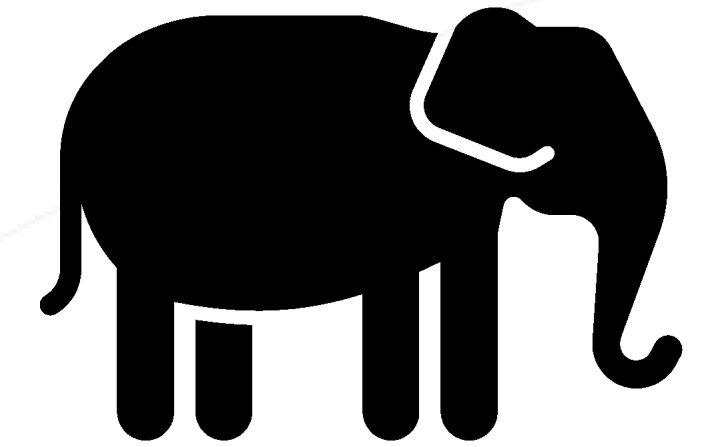
Pac, Tim, and Raymond, Dick Jr., "Remedial Musings" (2023)

June 4, 2024



*Those who cannot remember the past
are condemned to repeat it.
- George Santanyana*

Caveats

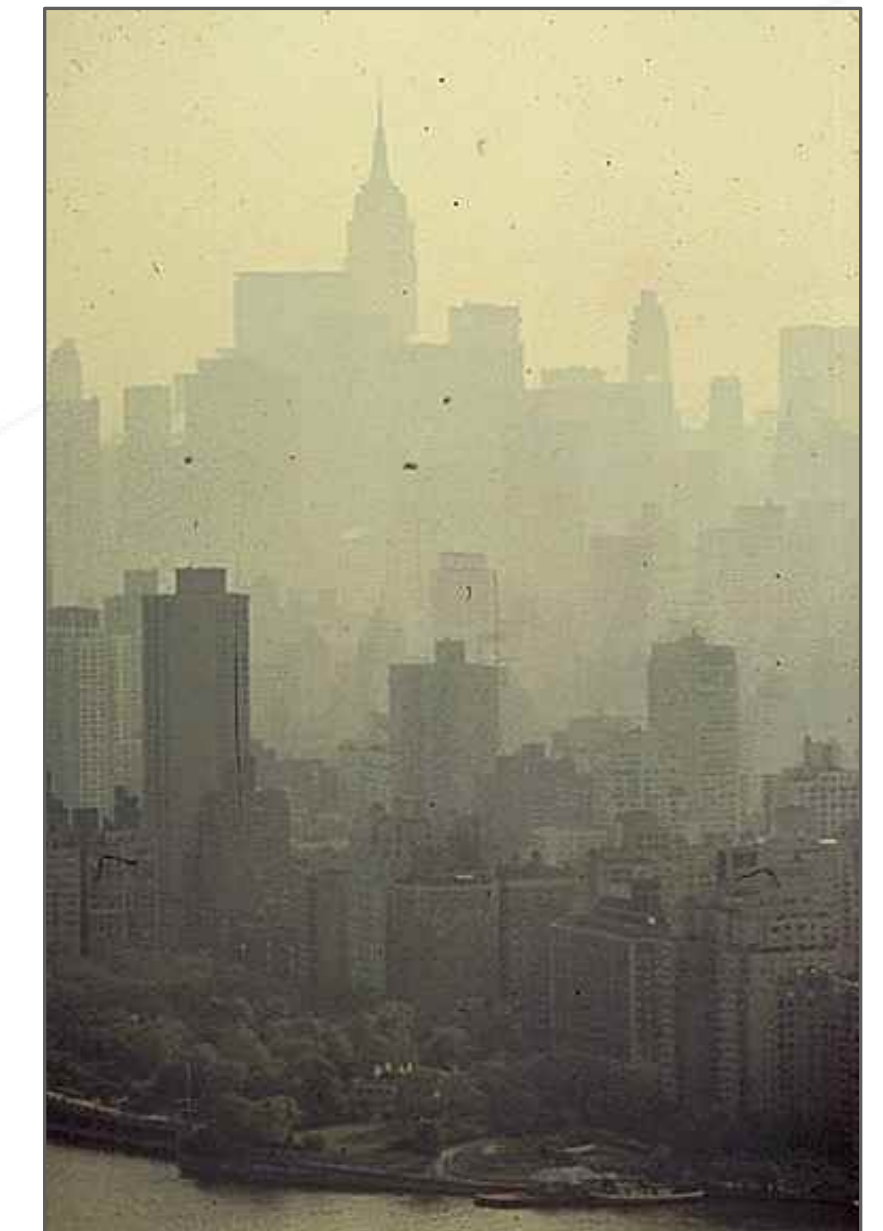
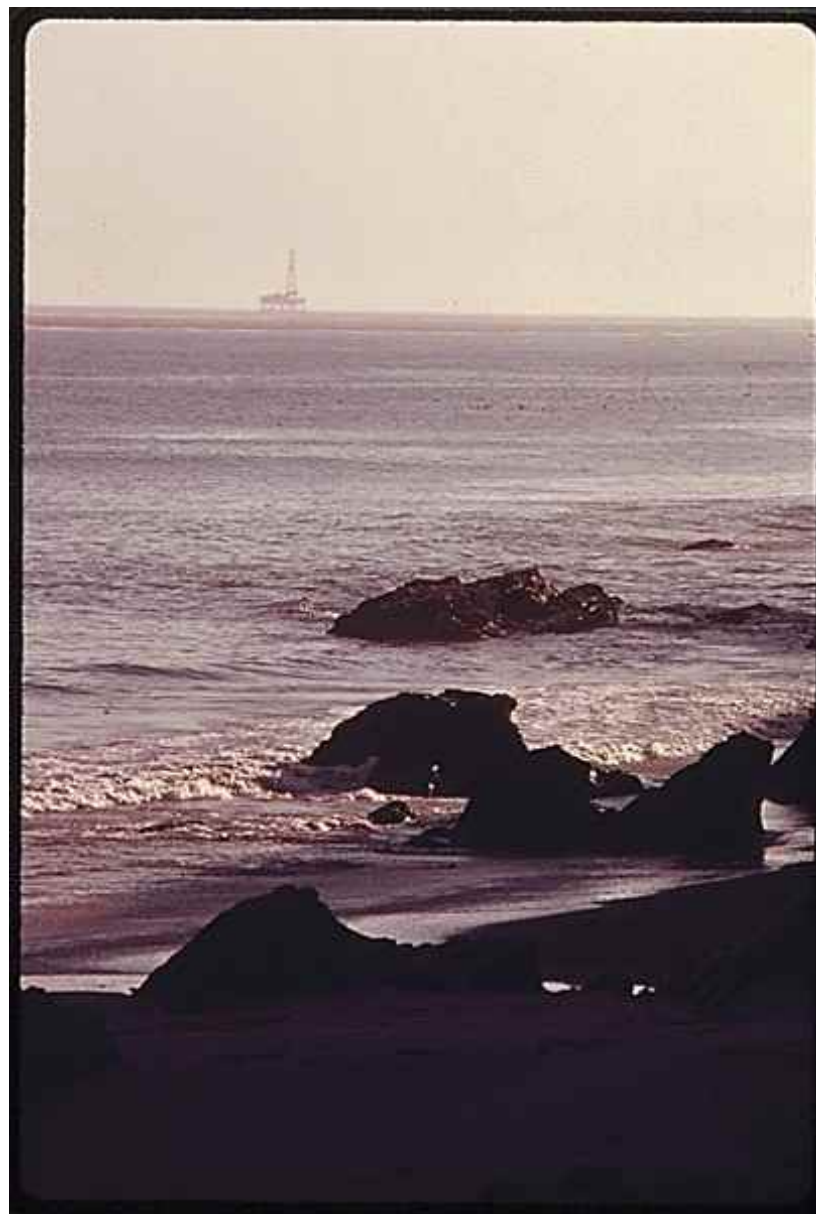


- Opinions expressed are personal
- Focus is on the United States' development
- Recognize there are deviations and omissions (e.g., EJ)
- Sprinkling of federal laws included, no discussion of state programs
- Focus on commercialized generally available technology
 - R&D always ongoing but normally proprietary (i.e., non discoverable)
 - academic research developed approaches, many not commercialized
 - patented processes stop/slow technology development
 - limit discussion of “fad” technologies

Goal is not to be a history lesson, but to provide context, framework, and motivation

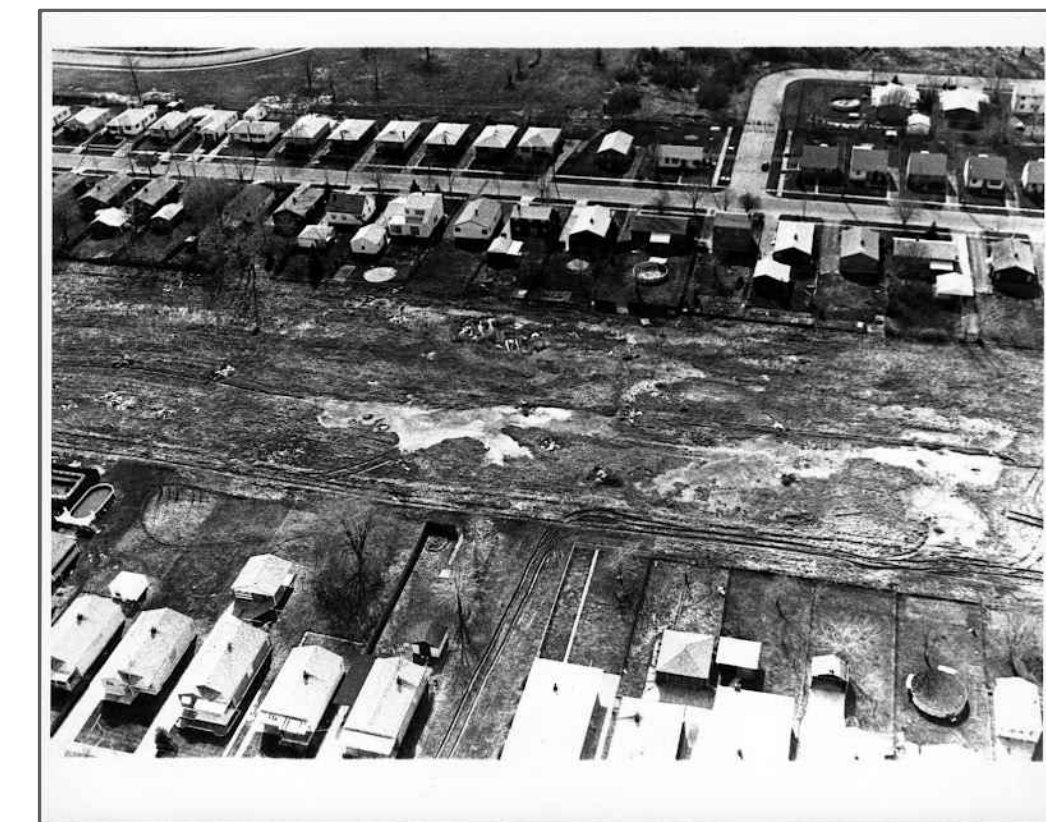
Prior to 1950...

- Smog and air pollution (1940 - 1960's) were major concern
- Very little energy focused on environment
- Uncontrolled open burn dumps were “state-of-the-art”



Then in the 1960's...

- The environment pushed back:
 - Agent orange (1961 - 1971)
 - Santa Barbara Union Oil spill, CA (1969)
 - Cuyahoga River fire, OH (1969) – 14X
 - Love Canal (1969)
 - Valley of the drums, KY (1969)



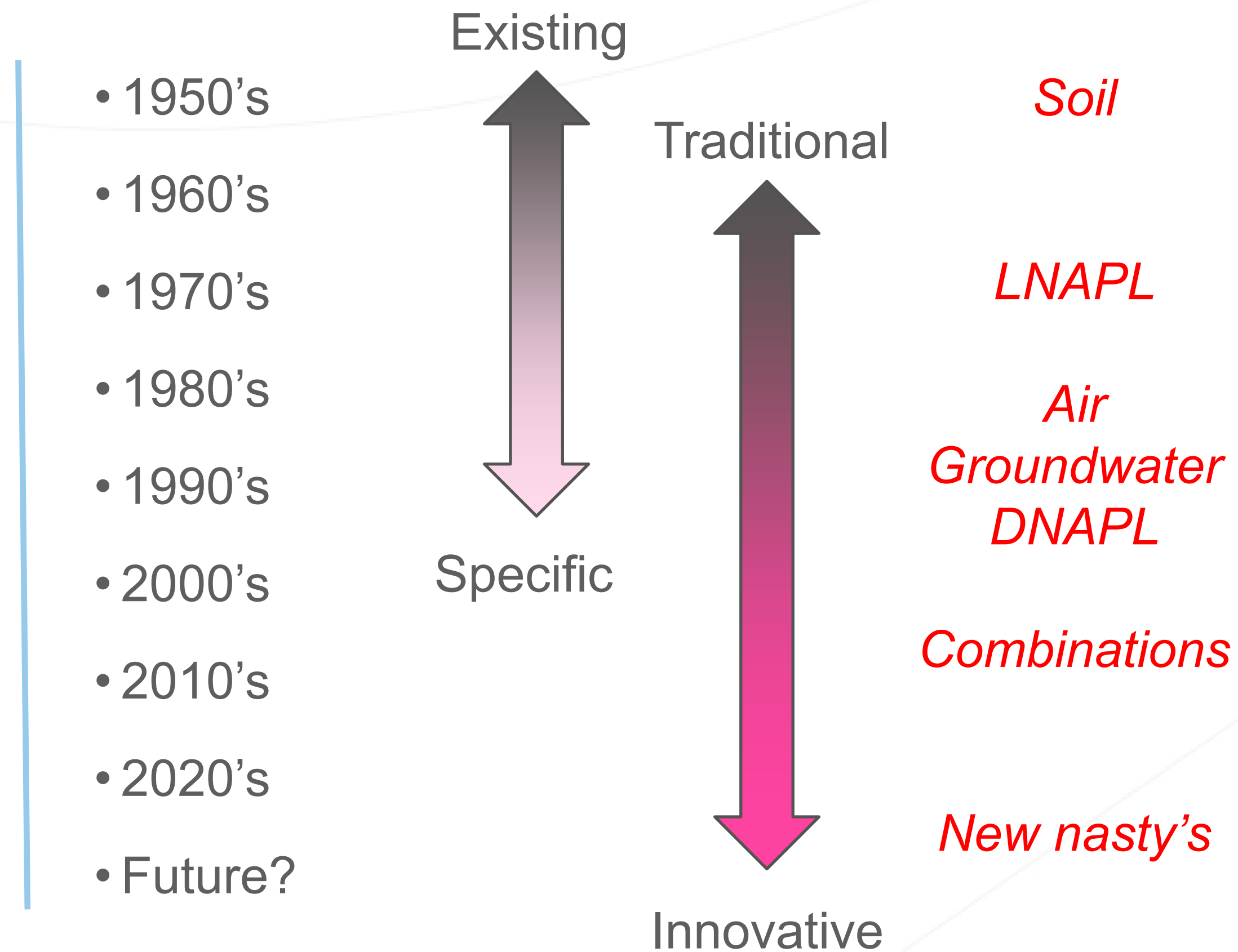
By the 1970's had we learned...?

New recognition, but learnings have not proven universal...

- Times Beach, MO (1972)
- “A Civil Action,” Woburn, MA (1978)
- Bhopal toxic cloud, India (1984)
- Burn pits in Afghanistan and Iraq (1990, 2001)
- Train derailment, CA (1994)



Birth and Genesis of Remediation

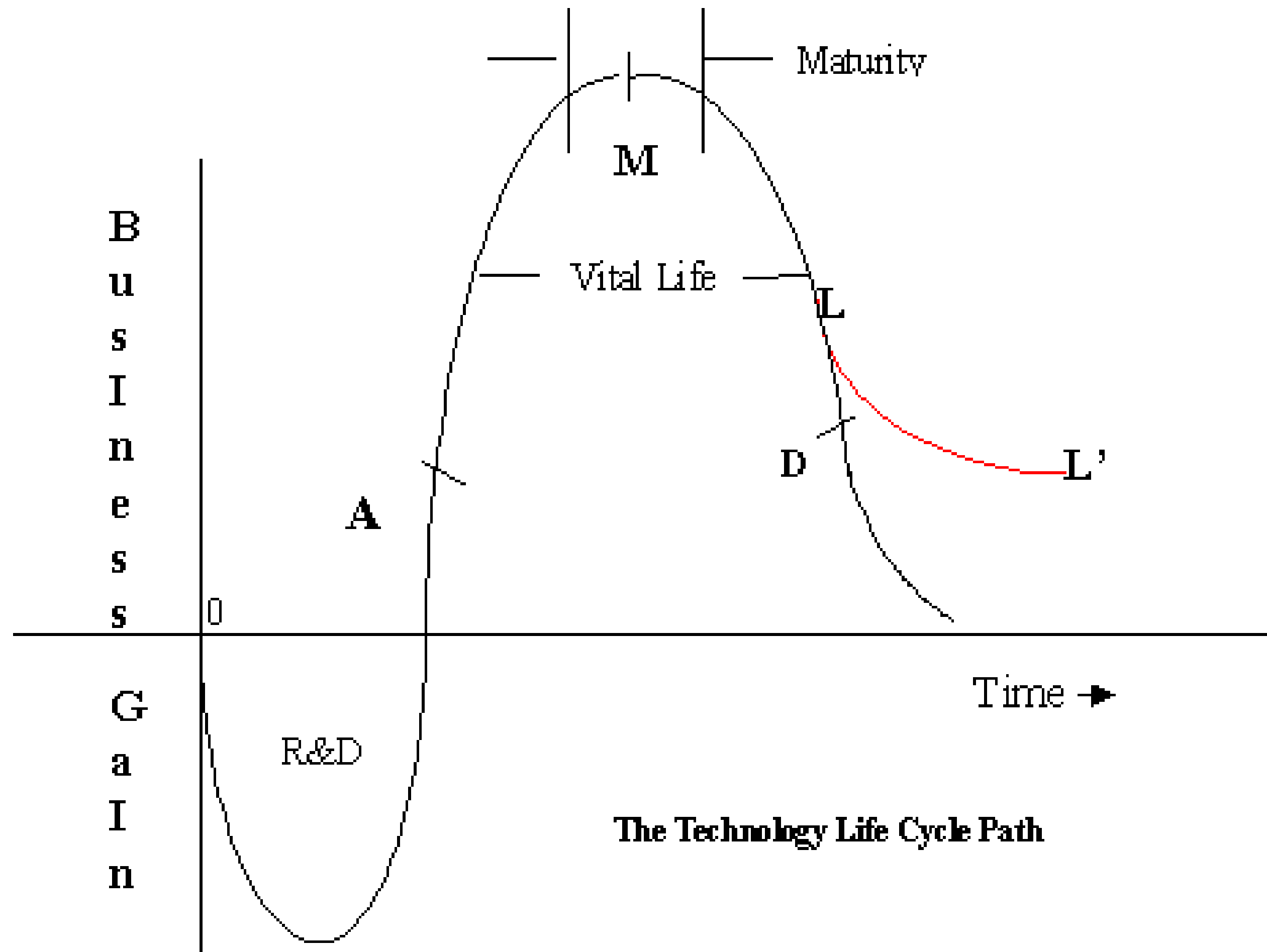


Remediation as a “practice” didn’t exist but borrowed existing technologies and practices from:

- oil field
- drinking water
- wastewater treatment
- general industries

As knowledge grew approaches became increasingly sophisticated and relevant

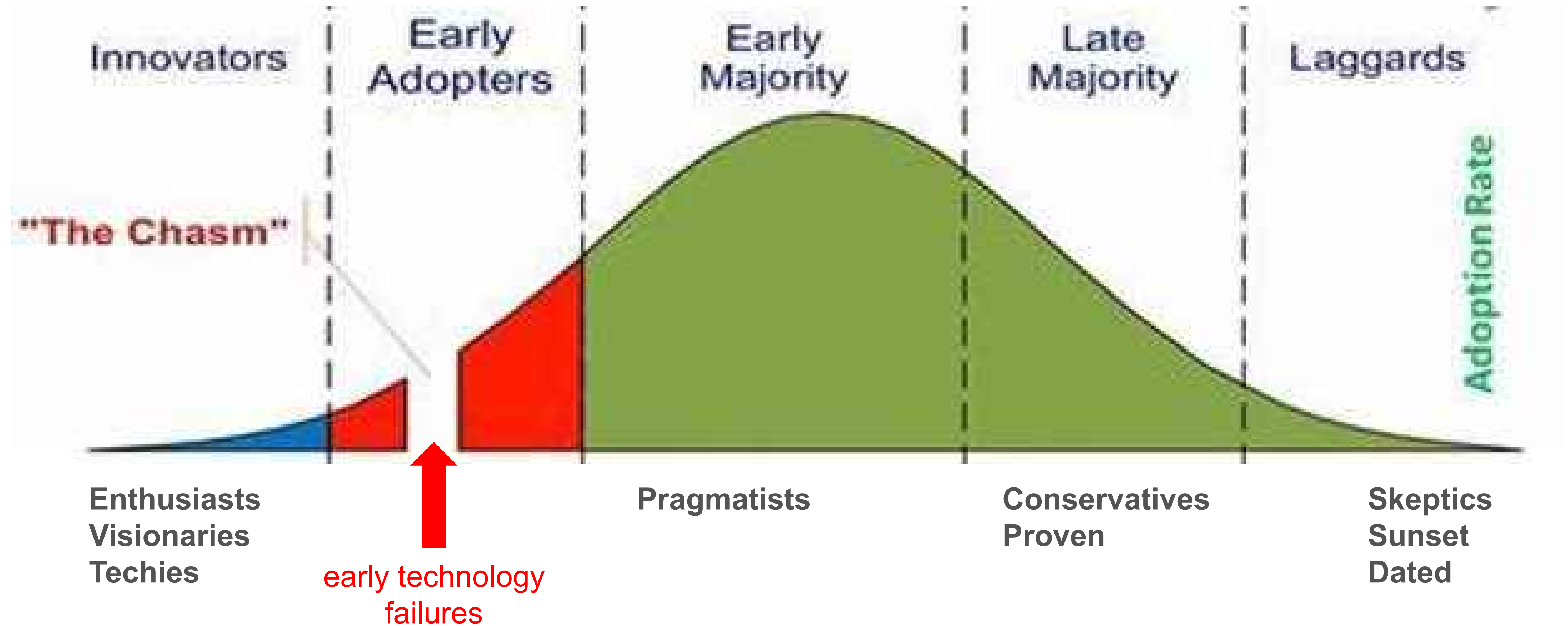
Technology Life Cycle (TLC-Curve)



- **Innovation** – R&D (cost), emergent, “bleeding edge”
- **Ascent** – new, adoption, syndication, profitable, “leading edge”
- **Maturity** – traditional, multiple players, diffusion, saturation
- **Decline** – substitution, competition, “next new thing,” stable base?
- Additional protections provided by
 - patents
 - trademarks
 - licensing
- Old technologies never really cease (**L'**)

Source: Wikipedia after Kondratieff, The Major Economic Cycles (1925)

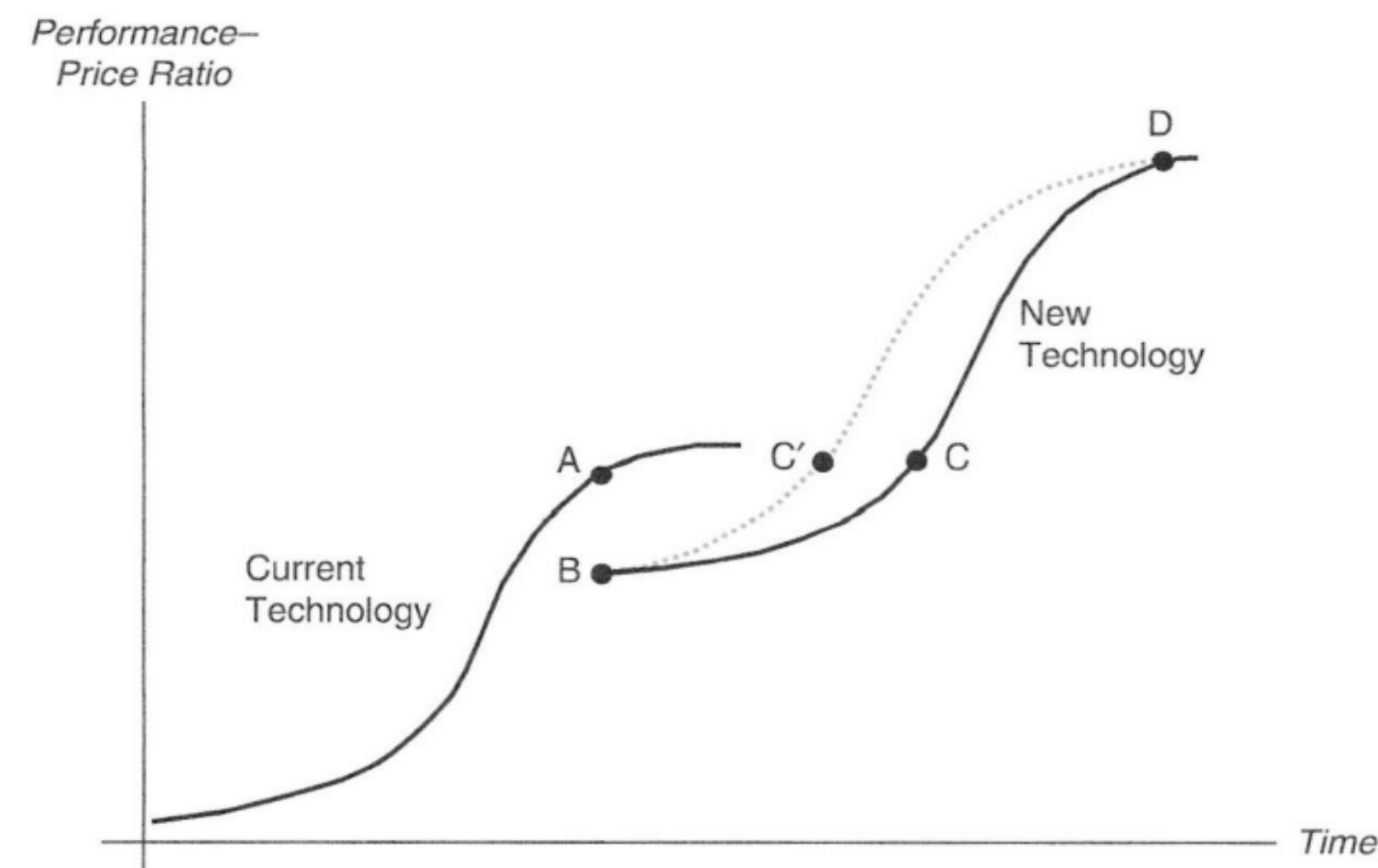
Technology Adoption



Source: Moore, Geoffrey A, Crossing the Chasm (1991) after Rodgers, Everett, Diffusion of Innovations Theory

Technology Life Cycles

Technology Life Cycles, Fig. 2 Life-cycle market failure: generic technology



Source: Tassey, Gregory, Technology Life Cycles, Encyclopedia of Creativity, Invention, Innovation and Entrepreneurship Carayannis, Elias G. (ed.) 2020)

The History of INNOVATION CYCLES

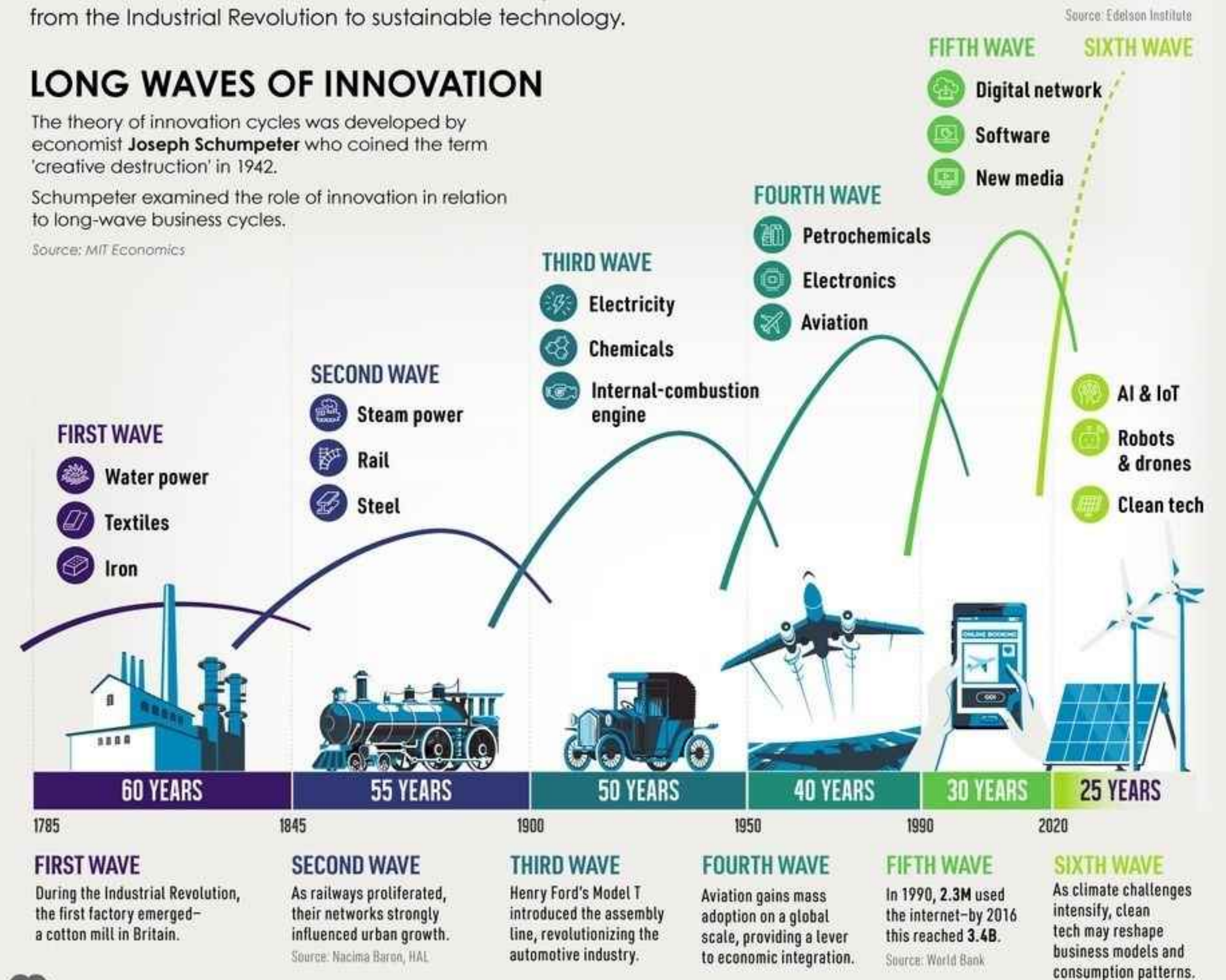
Below, we show waves of innovation across 250 years, from the Industrial Revolution to sustainable technology.

Source: Edelson Institute

LONG WAVES OF INNOVATION

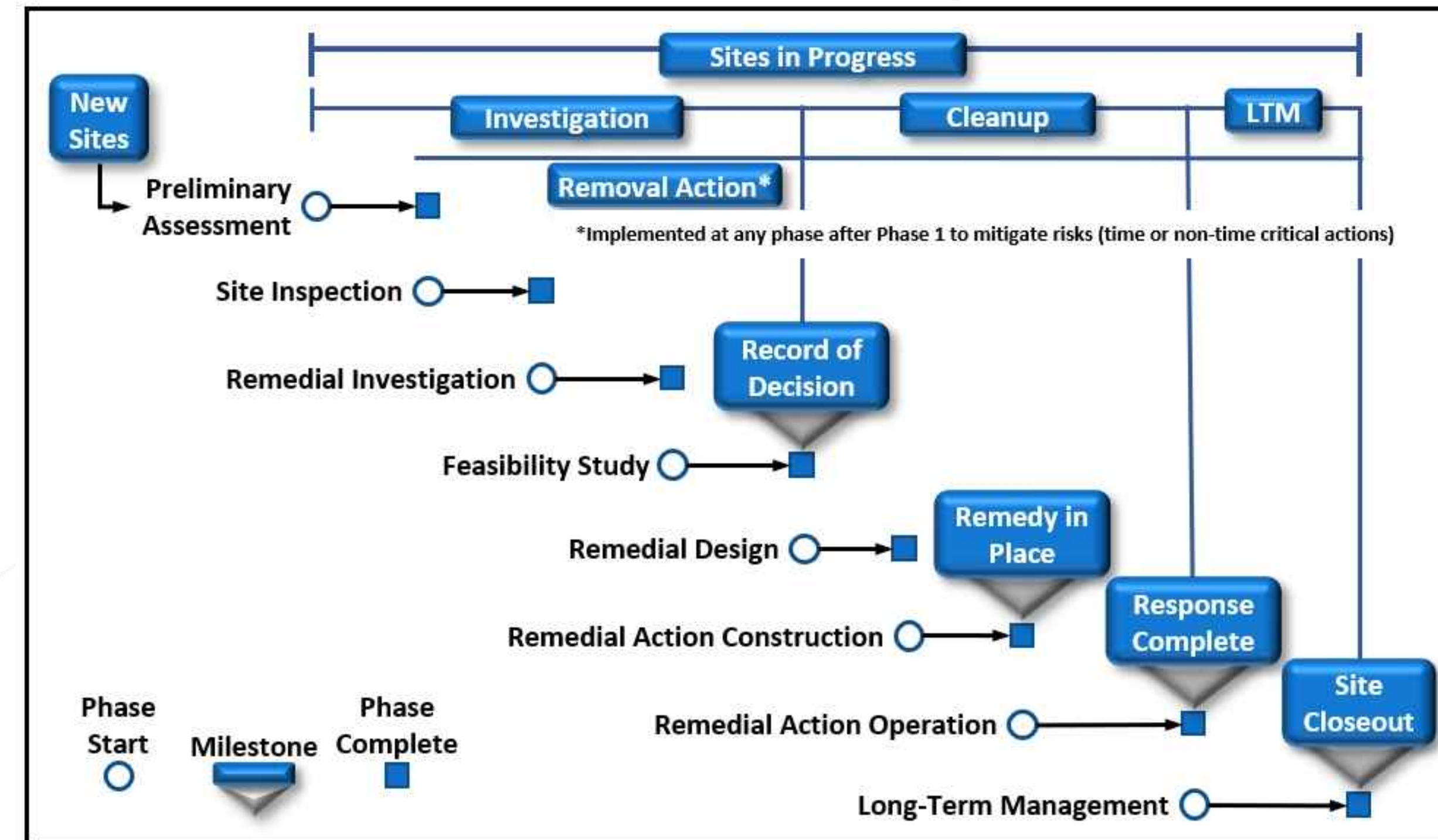
The theory of innovation cycles was developed by economist **Joseph Schumpeter** who coined the term 'creative destruction' in 1942. Schumpeter examined the role of innovation in relation to long-wave business cycles.

Source: MIT Economics



Reliance on Enforcement is Not a Solution

- Enforcement is not forward looking, must follow some incident, inaction or noncompliance
- Jurisdiction
 - federal vs. state vs. local
- Delays can be extensive
 - formulation of regulatory bodies – who
 - litigation by affected/interested parties
 - costs and delays
 - cynical view
 - environmental fairness (crime fit the punishment)
- Self regulation - industry will do the right thing
 - will it?



Reliance on Enforcement is Not a Solution

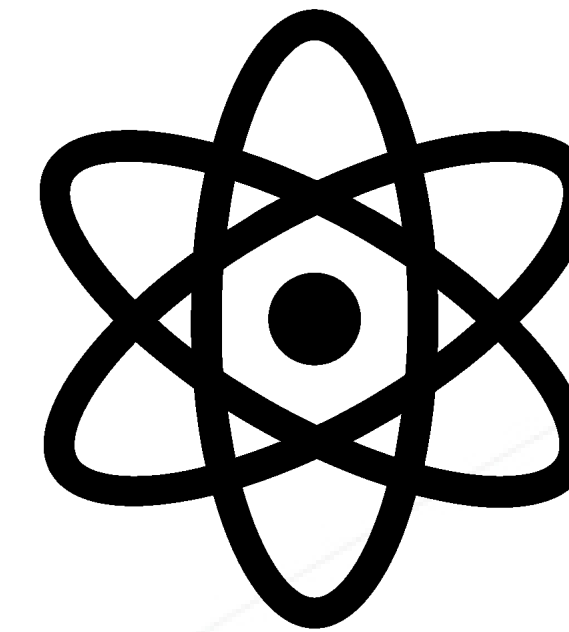
And the journey begins – decade by decade



COLOR KEY

- red – relevant context
- black – remediation history
- blue – regulatory statutes
- green – books and film
- purple – interesting context

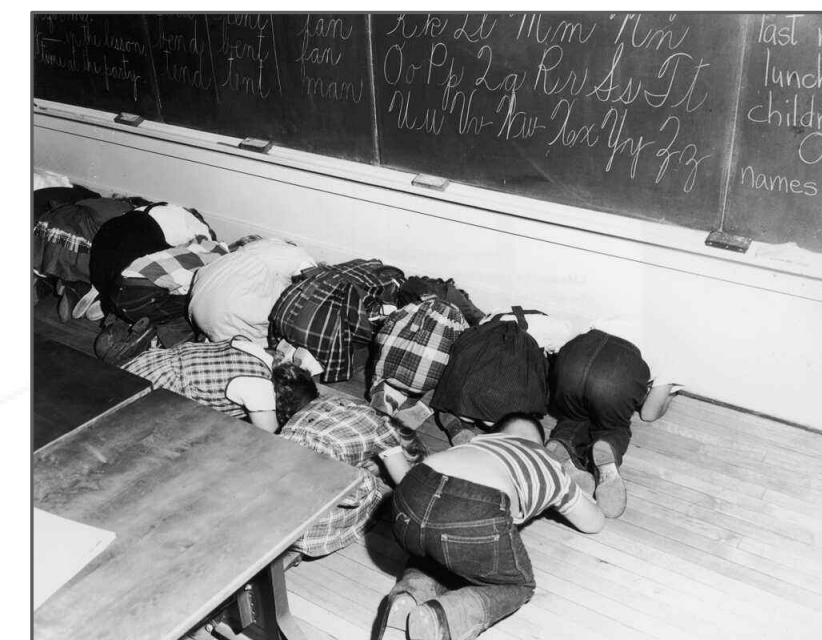
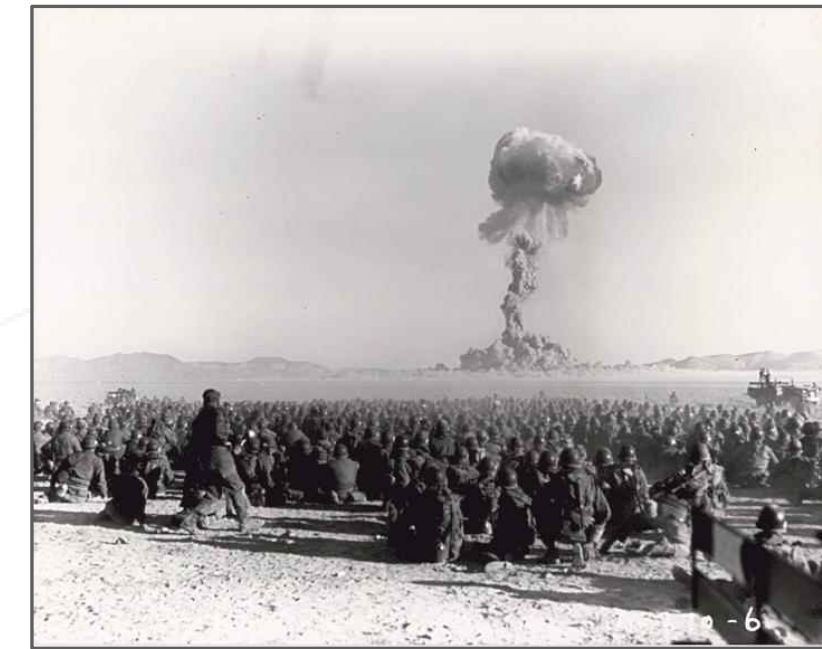
1950's Backdrop – Post World War II “Boom”



- WW I (1914-1918) toxic gases
- Leaded gasoline (1920's-1996)
- First nuclear land test (1945) followed by Hiroshima and Nagasaki
- Post WW II (1942 – 1945)
- Turing test (1950)
- Korean police action (1950-1953)

Start of the Cold War, I Love Lucy, The Honeymooners, rock n' roll, Puerto Rico, MAD magazine, Crick & Watson DNA model, frozen TV dinners, micky mouse club, McDonalds, Sputnik, NASA, hula hoops, baby boomers, racism and segregation, suburbanization

- David Thoreau, Walden (1854)
- Gilbert Plass, The Carbon Dioxide Theory of Climatic Change (1955)

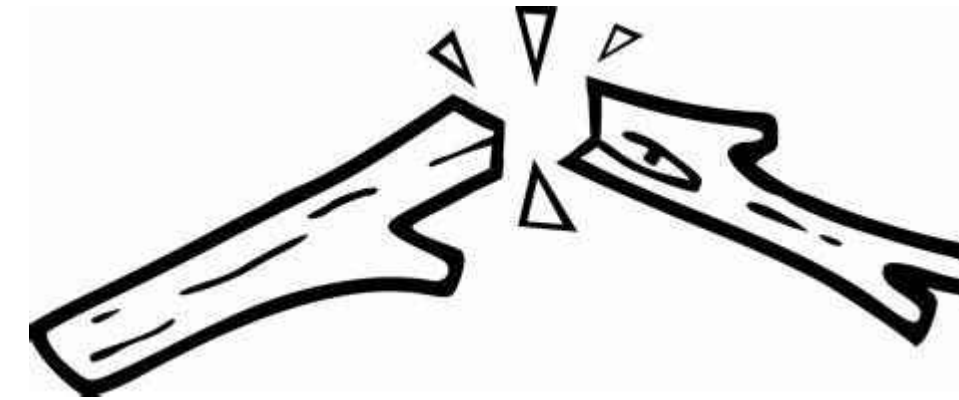


1950's Remedial Technologies (limited)

- **Reuse** - hand me downs, scrapyards
- **Do nothing** - Fresh Kills landfill (1948-2001)
- **Landfilling** - low areas, wetlands, mining
- **Open burning** - piles, dumps, barrels
- **Ocean dumping**
- Atomic Energy Act (NEPA, 1946)
- Air Pollution Control Act (APCA, 1955)



1960's Backdrop – Splintering

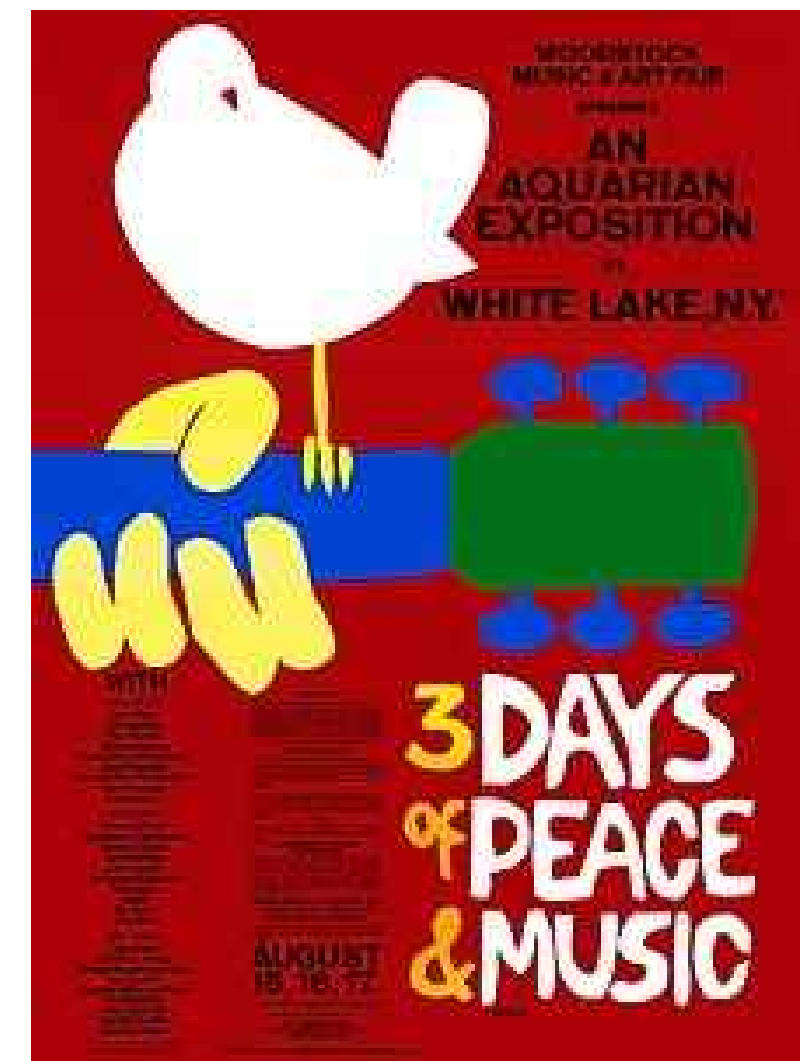


- Overhauls to solid waste practices
- Early environmentalism
- Recycling starts

“New Frontier” & the “Great Society,” Berlin Wall construction, Cuban missile crisis, Bay of Pigs, Beatles in the UK, Wal-Mart, Kennedy assassination, Voting Rights Act, MLK march, Vietnam War, Civil Rights Act, Star Trek, Rolling Stone, heart transplant, moon landing, ARPANET, Sesame Street, Summer of Love

- Rachel Carson, Silent Spring (1962)

To understand the living present, and the promise of the future, it is necessary to remember the past.
- Rachel Carson

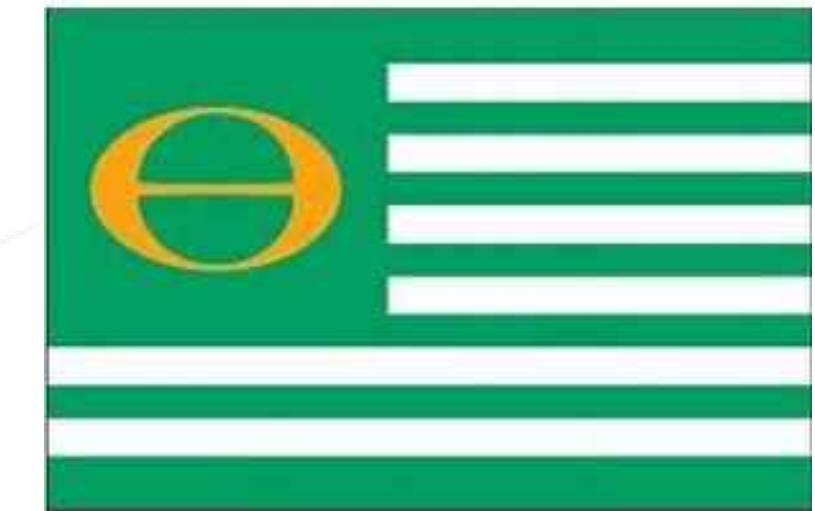


1960's Remedial Technologies (waste)

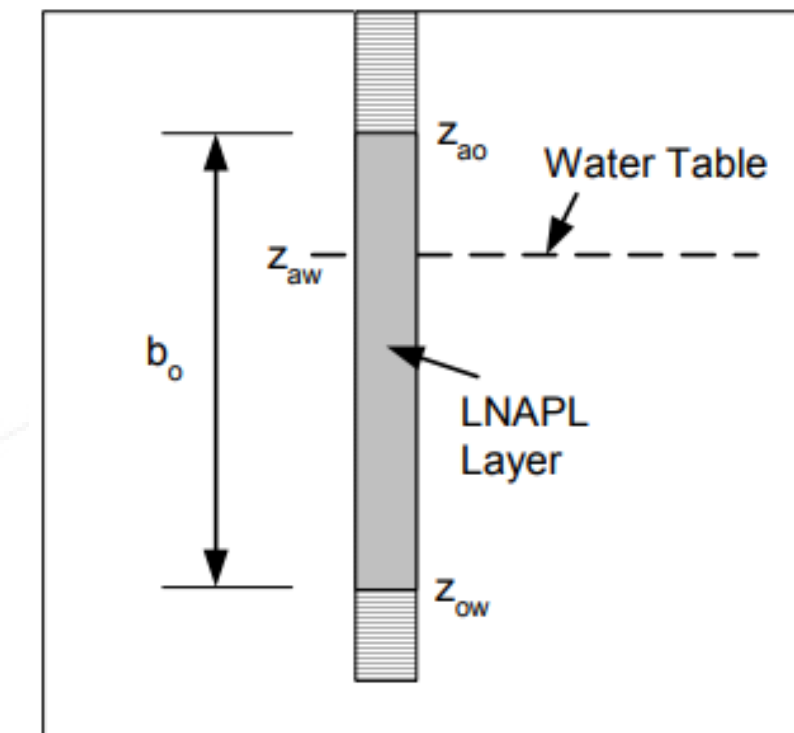
- **Sanitary landfill** and **incineration**
- **Landfarming** - oily wastes
- **Soil excavation** – excavate to the water table (end of contamination?)
- **Onsite storage and disposal**
- **Capping**
- Clean Air Act (CAA, 1963)
- Solid Waste Disposal Act (SWDA, 1964)
- National Environmental Policy Act (NEPA, 1969)



1970's Backdrop – information age



- Landfills filling up – disposal battles
- Earth Day (1970)
- Creation of EPA (1971)
- Oil crisis (1973)
- “Toxic tort” (chemical harm)
- Complexities in hydrocarbons
- “Apparent” petroleum thickness
- Groundwater impacts
- Regulation of carcinogens (1978) – benzene
- Three-mile Island (1979) – nuclear apprehension



Apollo 13, watergate, jaws, apple computer, space invaders, battle of the sexes, end of Vietnam War, space shuttle, Trans-Alaskan pipeline, think global / act local, microprocessors

1970's Remedial Technologies (humble start)

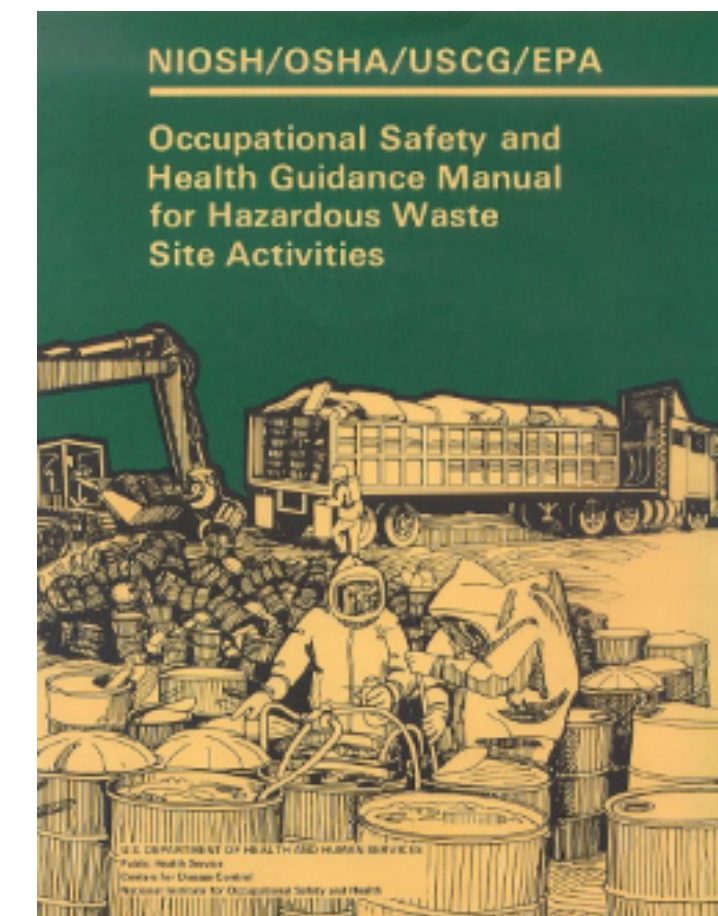


- **Free product recovery** – skimmers (passive/active), bailing, sorbent
- **Bioreactor** (1970) – landfills, vessels
- **In-Situ Aerobic Bioremediation** (1972)
- **Ex-Situ Aerobic Bioremediation** – soil piles, composting
- **Pump and discharge** – NPDES or O/W seps (1972), off-Site disposal
- **Zero Valent Iron** (1972, ZVI) – macro
- **Incineration** ($> 1,200^{\circ}$ F, \$\$\$\$)
- Clean Air Act Amendments (CAA, 1970)
- Clean Water Act (CWA, 1970)
- Occupational Safety and Health Act (OSHA, 1970)
- Safe Drinking Water Act (SDWA, 1974)
- Resource Conservation and Recovery Act (RCRA, 1976)
- Toxics Substances Control Act (TSCA, 1976)



1980's Backdrop – mobile communications

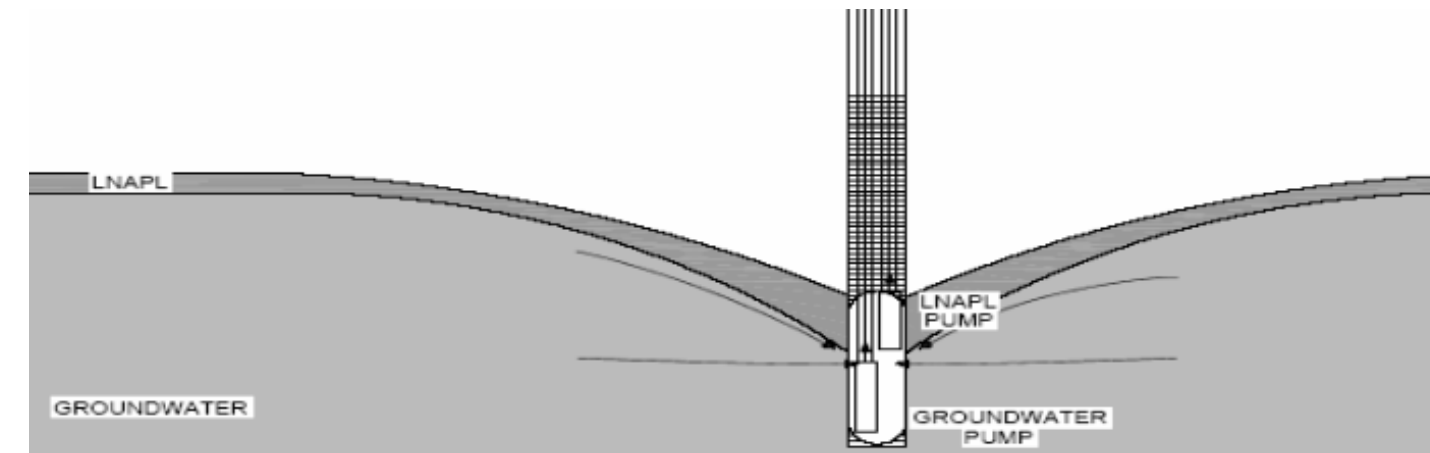
- **Underground Storage Tanks (UST, 1984)**
- [OSHA Guidance Manual for Hazardous Waste Site Activities \(1985\)](#)
- Accurate **mass estimates** of LNAPL
- Recognition of **chlorinated solvents, metals, pesticides**
- **Chernobyl explosion (1986)**
- **LUST guidance (1988)** - free product recovery
- **Site characterization methods** – standardization ?
- **Heat waves and needles washing up on shore (1988)**
- **Risk Assessment** - $R = f(\text{Hazard} * \text{Dose}) < 10^{-6}$, later RAGS
- **Exxon Valdez oil spill (1989)**
- **Geophysics** – surface gravity, magnetics, seismic, resistivity



Mount Saint Helens, James Watt, John Lennon shot, olympic boycott, mainstream PC, MTV, AIDs, the computer is “man of the year”, compact disc players, Band Aid, Challenger disaster, end of Cold War, contact lens, The Simpson’s, mad cow disease, Tiananmen Square

1980's Remedial Technologies (treat water/air) **terra**systems

- **Pump & Treat (P&T)** – groundwater depression, total fluids, dual pumps, recirculation, infiltration, flushing, gradient modification
 - **air stripping**
 - **carbon adsorption**
- Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, “Superfund,” 1980)
- Solid Waste Amendments to RCRA (1984) – land disposal restrictions
- **Soil Vapor Extraction (SVE, TerraVac, 1984)**
- **Enhanced oxygen delivery** (1984, H_2O_2)
- **Slurry Walls** (1985)
- **In Situ Chemical Oxidation (ISCO), part 1** [peroxide, 1985, MFR]



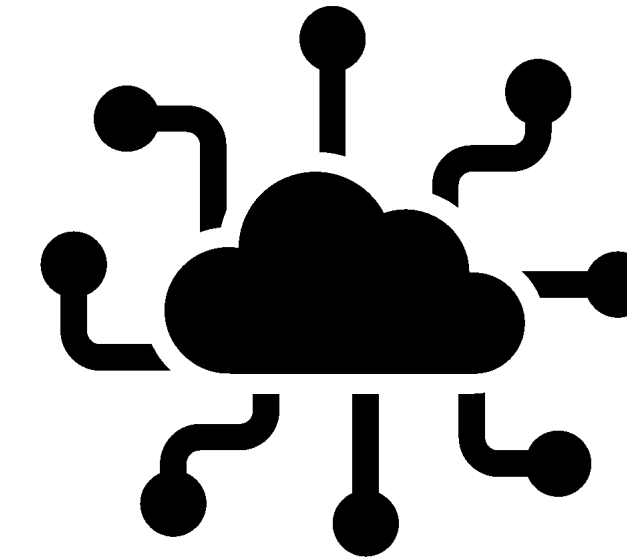
1980's Remedial Technologies (treat soil)



- **Soil Washing** (1986)
- Superfund Amendments and Reauthorization Act (SARA, 1986)
- Emergency Planning & Community Right-to-Know Act (EPCRA, 1986)
- **Zero Valent Iron (ZVI)** – meso
- **Steam Enhanced Extraction (SEE)**
- **Horizontal Wells** (1987)
- **Multi/Dual Phase (M/DPE 1989)**
- **Shallow Soil Mixing/Solidification** (1989)
- **Air Sparging** (1989, NH)

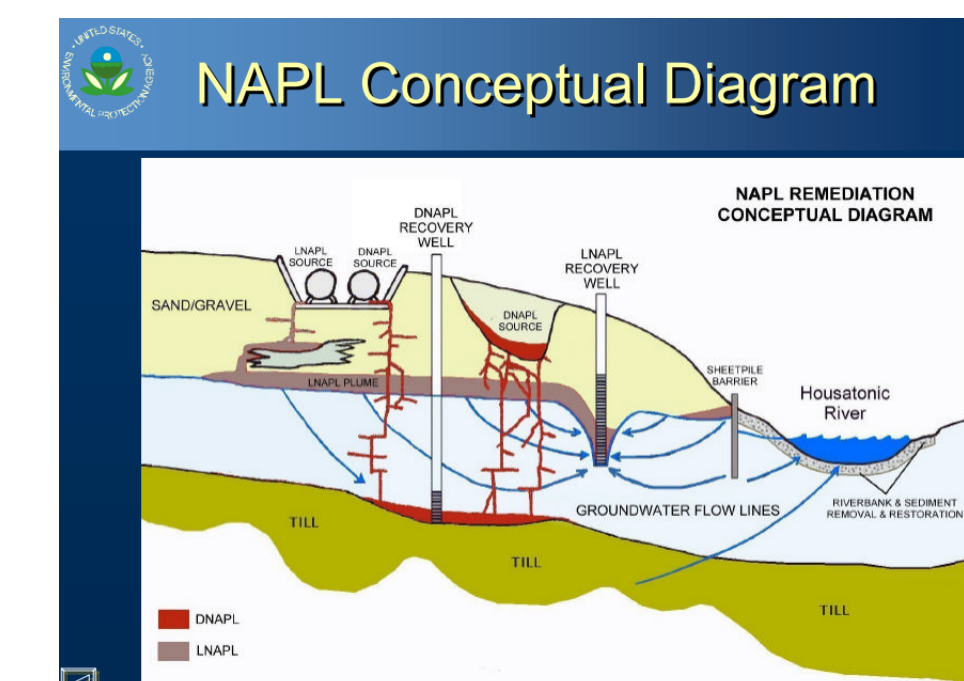
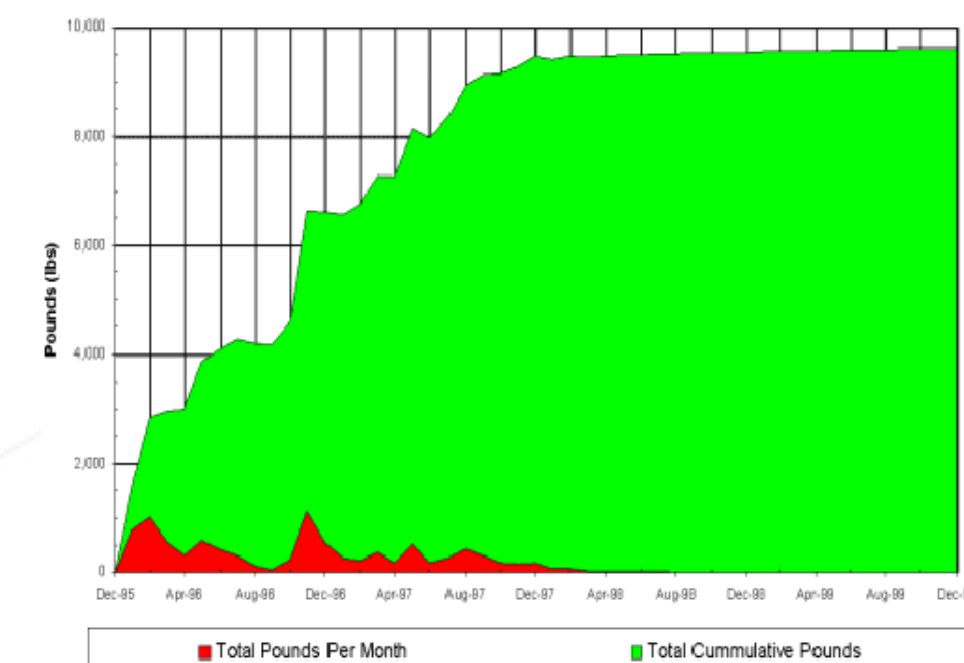


1990's Backdrop – Internet



- **HAZWOPER 1910.120 (1990)**
- **RBCA site closure - statistics**
- **Soil gas methods for delineation - sorbers**
- **Portable GC – lab to field**
- **Focus on mass vs. concentration - “rooster tail” & plume dynamics**
- **Differences in NAPL Flow**
- **Passive Diffusion bags (PDBs) (1998)**
- **Complexity is the norm – ~~isotopic and homogenous~~**
- **Vapor Intrusion (VI)**

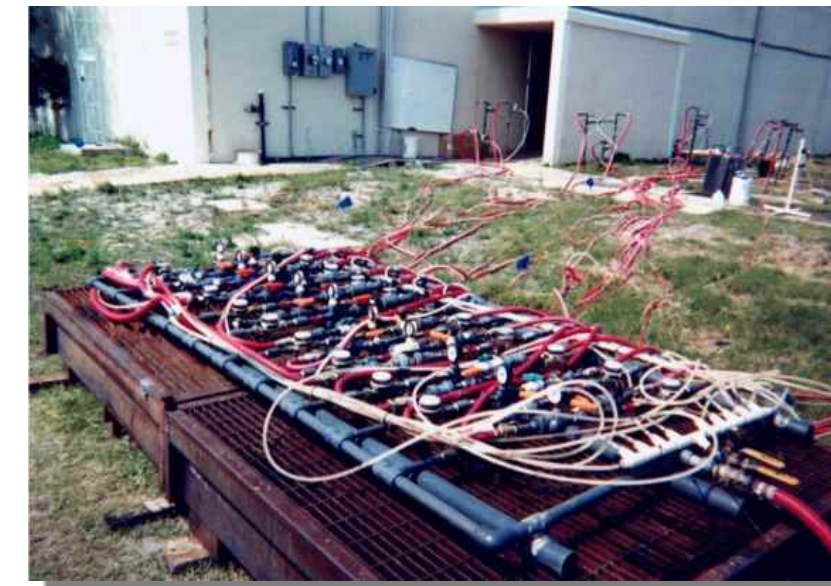
Gulf War, reunification of Germany, USSR collapse, the internet, EU, NAFTA, Chunnel, Ebay, Harry Potter, cloned sheep, Google, Napster, Euro, Kyoto Protocol



1990's Remedial Technologies (1/2, flourish)



- **Anaerobic Bioremediation** (1992, DuPont)
- **Electrical Resistance Heating (ERH)** (1992)
- **Phytoremediation** (1993)
- **Biosparging and Bioventing** (1994)
- **In-Situ Chemical Reduction (ISCR)** [ZVI, CPS]
- **Fracturing** (1995) – pneumatic, hydraulic, blast
- **Vitrification** – nuclear materials
- **Clean Air Act Amendments (CAAA, 1990)**



1990's Remedial Technologies (2/2, growth)



- **Bioaugmentation** (1996, Dover AFB)
- **In Situ Chemical Oxidation (ISCO)**, part 2 [permanganate (1997), persulfate (1999)]
- **Surfactant Enhanced Product Recovery (SEPR)** (1997, Hill AFB)
- **Thermal** (1997) [SEE, DUS, 6-P]
- **Monitored Natural Attenuation (MNA)** (1999)
- **Lasagna** (1999)
- **Barriers / Walls** – PRBs, funnel + gate, cutoff, slurry
- **Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA)** (1996)



Bioaugmentation for Accelerated In Situ Anaerobic Bioremediation

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A successful anaerobic bioaugmentation was carried out on a trichloroethene (TCE)-contaminated aquifer at Dover Air Force Base, DE, using a microbial enrichment culture capable of dechlorinating TCE to ethene. A hydraulically controlled pilot system 12 x 18 m was constructed 15 m below ground surface in an alluvial aquifer to introduce nutrients and substrate into the groundwater. Ambient TCE and cis-1,2-dichloroethene (cDCE) concentrations in groundwater averaged 4800 and 1200 µg/L. The pilot operated for 568 days. Results by day 269 confirmed previous laboratory work showing that dechlorination did not proceed past cDCE. By this time, most of the TCE was dechlorinated to cDCE, and cDCE was the predominant contaminant. An ethene-forming microbial enrichment culture from the Department of Energy's Pinellas site in Largo, FL, was injected into the pilot area. After a lag period of about 90 days, vinyl chloride and ethene began to appear in wells. The injected culture survived and was transported through the pilot area. By day 509, TCE and cDCE were fully converted to ethene.

Introduction

Chlorinated solvents are widely used as solvents, cleaners, and degreasing agents. As a result of spills and past disposal practices, these compounds are contaminants in groundwater, soil, and sediments. Standard remedial approaches have proven to be ineffectual and costly at removing these substances from the environment. Within the last 15 years, basic research on natural microbial dechlorination mechanisms has suggested that the destruction of chlorinated

and government agencies. This paper describes the RTDF's application of anaerobic microbial dechlorination of chlorinated solvents in a pilot study at Dover Air Force Base (AFB), DE. In this process, electron donors and/or nutrients are added to the subsurface to create anaerobic conditions and to stimulate organisms that can completely reductively dechlorinate chlorinated solvents.

Initially, substrates and nutrients were injected into the groundwater to stimulate indigenous microbiology, and an ethene-forming enrichment culture was injected into the groundwater later. The observed biodegradation confirmed experiments by Harkness et al. (2, 3) which showed that indigenous Dover AFB bacteria were unable to dechlorinate trichloroethene (TCE) beyond cis-1,2-dichloroethene (cDCE); that the nonindigenous bacterial consortium added to the subsurface was able to reductively dechlorinate TCE and cDCE to ethene; and that the injected culture survived in the new environment and was physically transported throughout the pilot study area. Stapleton et al. (4) characterized Dover AFB microbial populations in contaminated and uncontaminated sediments based on catabolic genotypes.

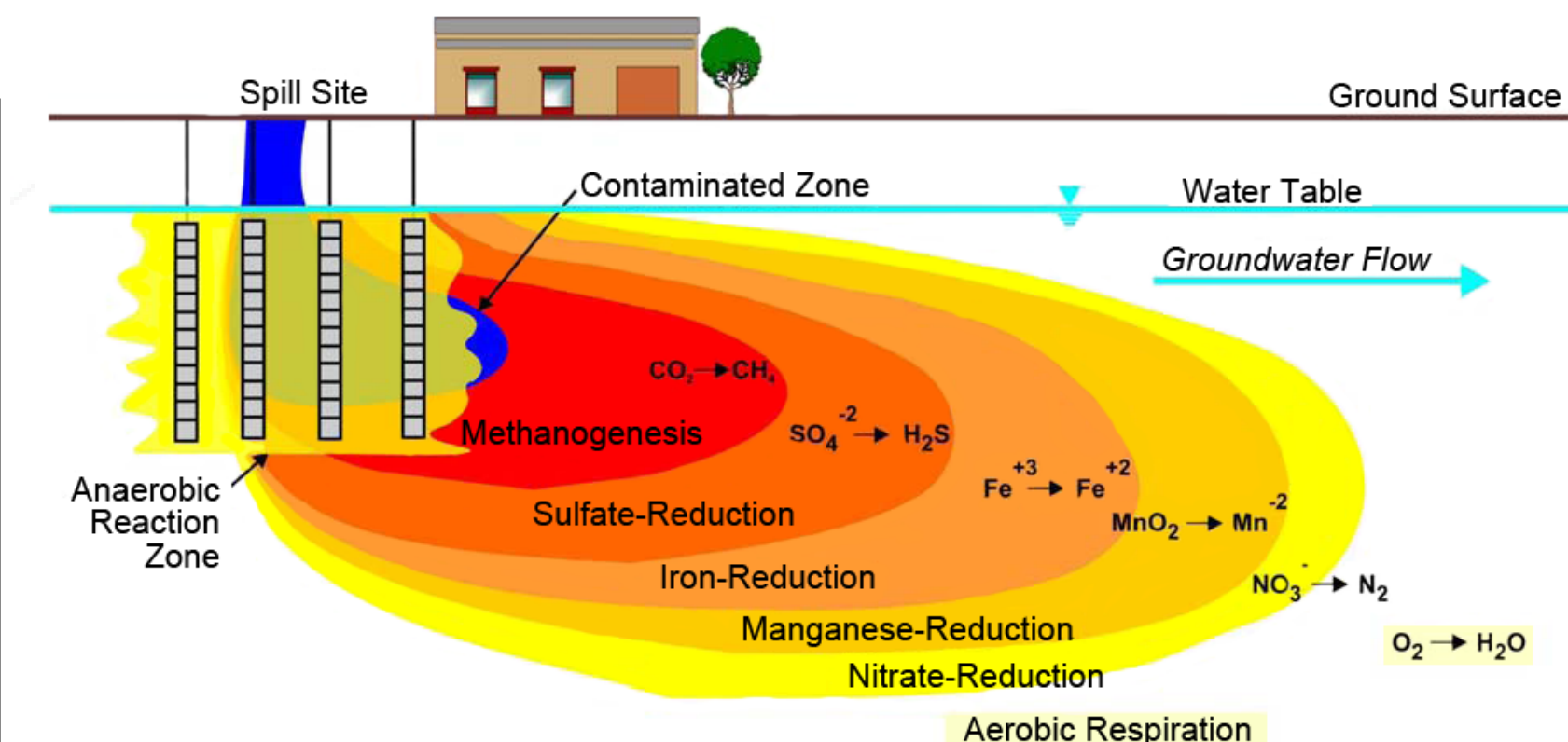
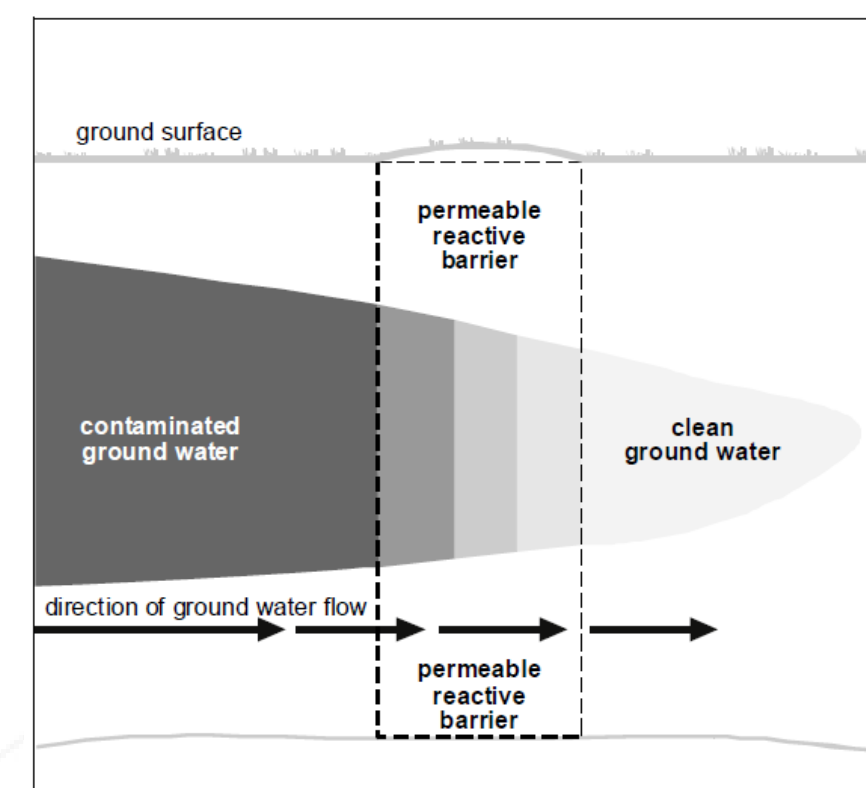
Methods

Physical Site Characterization. Dover AFB is underlain by sands and silts of the Pleistocene Columbia Formation that overlies the Miocene Calvert Clay aquitard (5). The pilot area was characterized as part of the Area 6 sitewide study conducted by the RTDF in March 1995 (6). Figure 1 shows the location of the pilot in relation to the contaminant plume. Groundwater velocity under natural nonpumping conditions is approximately 0.05 m/day. Total organic carbon (TOC) levels in the native soils were less than 1%.

Chemical Site Characterization. Historic maintenance and repair activities over approximately 50 years of operation at Dover AFB have resulted in solvent spills and subsequent groundwater contamination. Remedial investigations at the AFB have concluded that, except for source areas, solvent contamination is much more widespread in the deep zones of the shallow aquifer. Therefore, pilot activities focused on the deep zone. Sampling was conducted on monitor wells in and near the pilot area (Figure 2). A certified commercial laboratory determined the concentrations of chlorinated volatile organic compounds (CVOCs), TOC, major cations and anions (Table 1), and important geochemical parameters. Contaminant and geochemical data were used for designing the pilot feeding strategy and equipment.

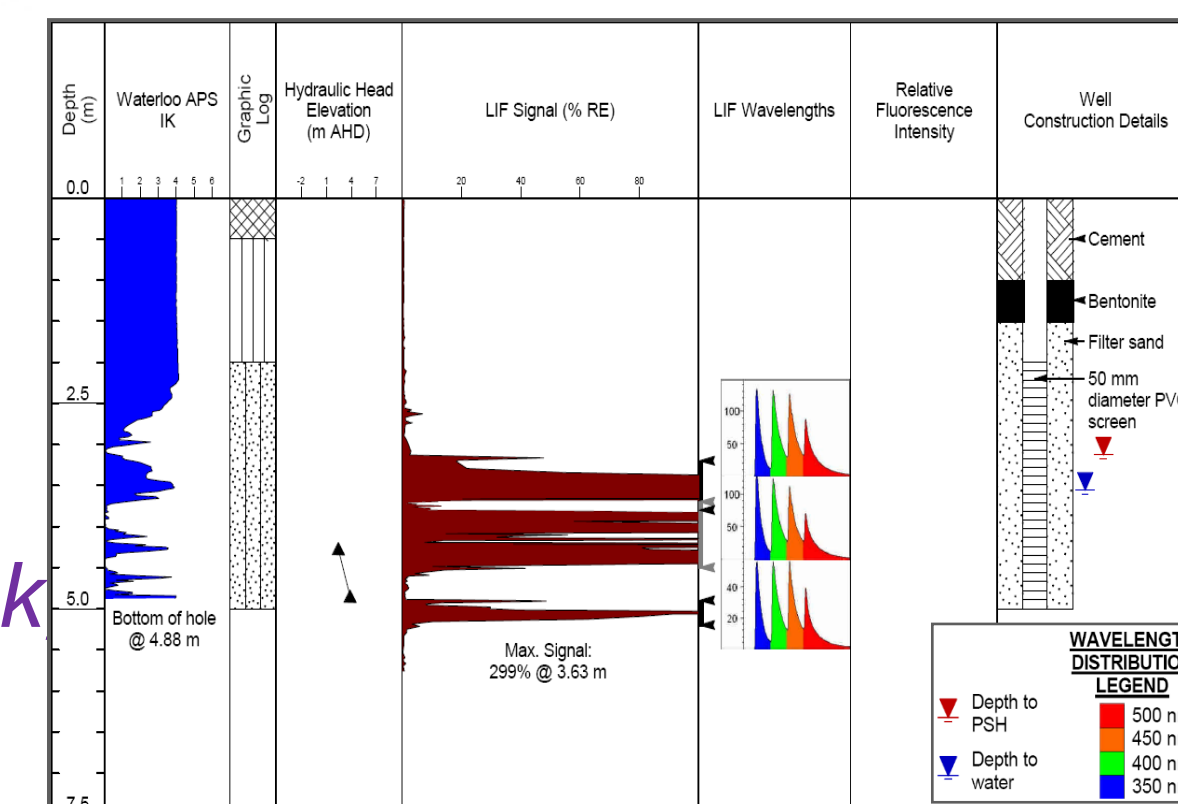
Groundwater Modeling and System Design. Groundwater flow and transport modeling was used as a tool to design the pilot system. The Columbia Formation was modeled as one unconfined aquifer system with three layers to determine the three-dimensional flow regime caused by pumping and to evaluate pilot system scenarios. The combined pumping rate determined by groundwater modeling was established at 11.6 L/min, 3.9 L min⁻¹ well⁻¹. Figure 2 presents the predicted groundwater flow lines for the final design. These were verified under operating conditions by using a bromide tracer. Details of modeling, design, and operation will be published separately.

Figure 2 also presents the plan view of extraction, injection,



2000's Backdrop – Climate Change

- September 11, 2001 disaster
- Waste to energy plants
- High Resolution Site Characterization (HRSC)
- Remedial optimization and fractured rock
- TRIAD approaches – quantity vs. cost
- Importance of integrated **Conceptual Site Model (CSM)**
- No “silver bullet” Technology
- Treatment trains
- New perspectives on the triple bottom line (2003)
- **Compounds Stable Isotope analysis (2005, CSIA)**
- **Plume cores** – (2005) 75% of mass in 5-10% of plume
- **An Inconvenient Truth (2006)**



*Terrorism, globalization, DHS created, Human Genome mapped, Iraqi War, Facebook
US rejects Kyoto protocol, iPhone, Deepwater Horizon, miracle on the Hudson,
drones, Hurricane Katrina, China overtakes US as largest GHG emitter*

2000's Remedial Technologies (combinations) **terra**systems

- **Cometabolism** (2000, Dover AFB)
- **BiRD** (2000)
- **Emulsified Zero Valent Iron** (EZVI, 2001, NASA)
- **In Situ Stabilization** (ISS, 2001)
- **Surfactant Enhanced ISCO** – SISCO (2002)
- **Trap and Treat** (2002)
- **Anaerobic bioremediation of DNAPL** (SABRE, 2003)
- In situ **sorption/sequestration** technologies – “improved” carbons, clays
- **EK methods** – DC electroosmosis
- **Combined methods** (2008)
- **Abiotic degradation** (2009) – iron minerals



What About Sustainability?

- “Sustainable Remediation” and formation of Sustainable Remediation Forum (SuRF) (2006)



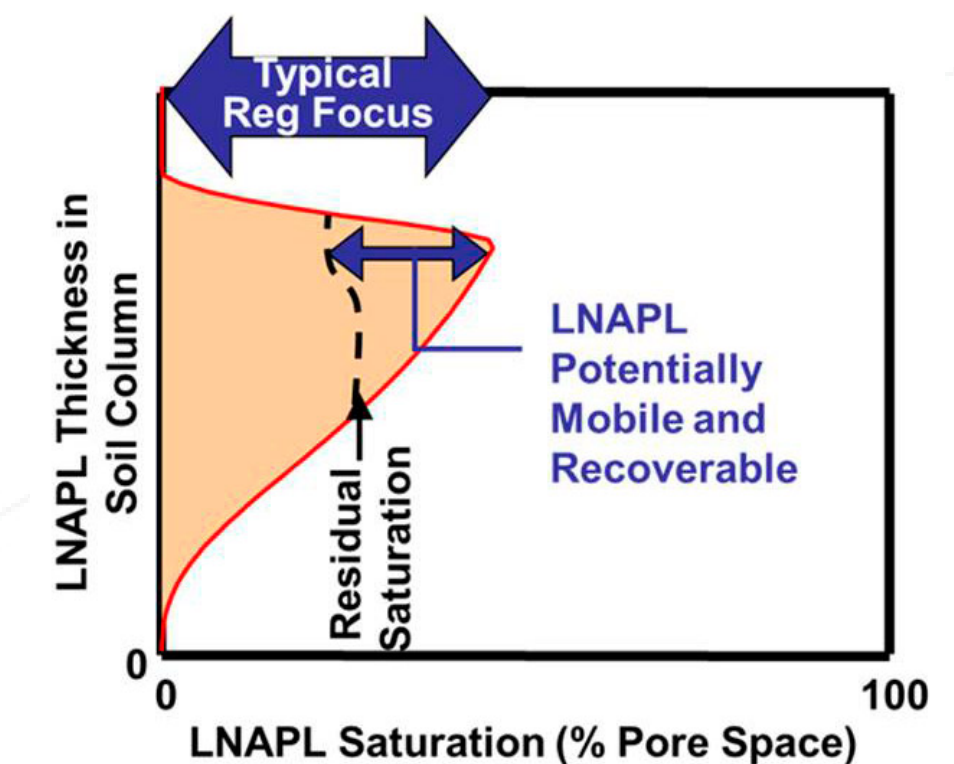
- Green Remediation (EPA, 2008)



2010's Backdrop – global tensions

- Fukushima disaster (2011)
- Microplastics
- Emerging contaminants – 1,4-D, PFAS, pharma, EDRs, ClO₄-...
- “Forever” chemicals – PFAS...
- Environmental Molecular Diagnostics (EMDs, 2010) - qPCR, RNA, ‘omics
- Environmental sequence stratigraphy (2017)
- LNAPL saturation and recoverability (2017)
- Data visualization – creating understandable complexity
- Big data
- Nano remediation?

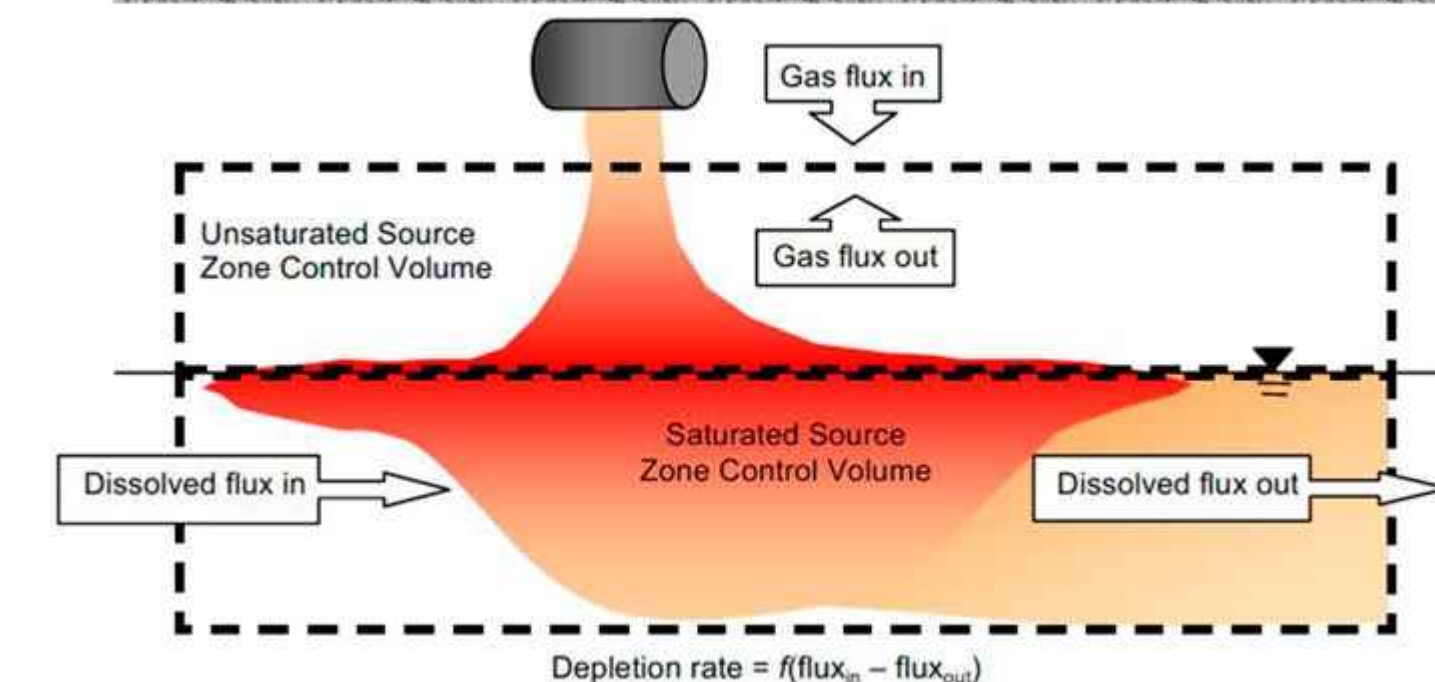
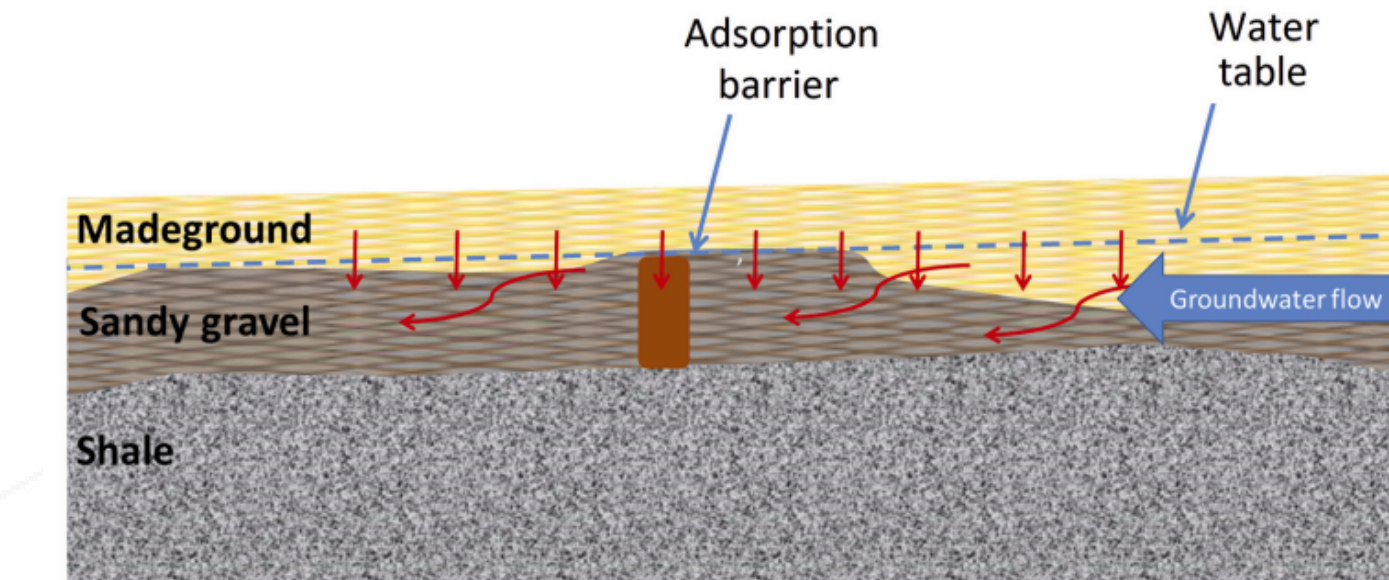
Hurricane Sandy, Boston Marathon bombings, Paris Agreement



2010's Remedial Technologies (sustainable)

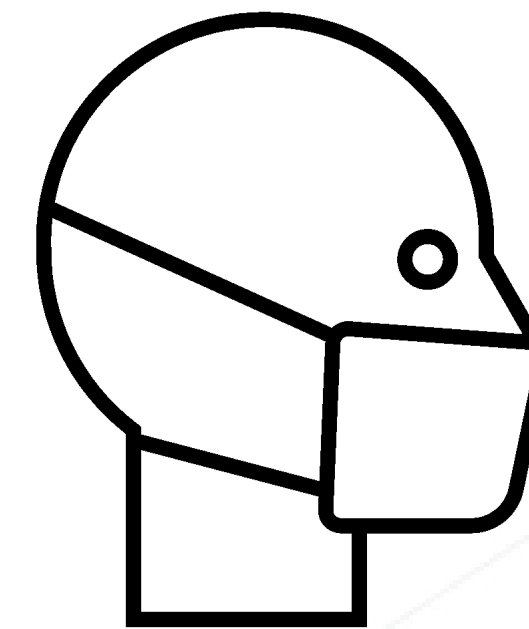


- **In-Situ Combustion** (2010)
- **Search and Destroy™** (2013) – combined HRSC/targeted injection
- **Adsorption Barriers** (2013) – colloidal iron
- **Natural Source Zone Depletion** (NZSD, 2015)
- **Multiple Sizes of Iron in EVO** (2015)
- **Liquid Activated Carbon** (2015)
- **Engineered biota** – synthetic biology
- **Expanded sustainable approaches** –
 - Vermiremediation - worms
 - Mycoremediation – fungi (around previously but never commercialized)
 - Enzyme Mediated Bioremediation – biocatalysts (2019)
 - Phycoremediation – macro and micro algae
 - Phytoremediation – use of other plants



2020's Backdrop – COVID, global pause

- Energy – fusion power, battery densification, hydrogen
- Large scale carbon sequestration
- Space travel
- Quantum computing
- Virtualization – AR
- Genomic manipulation
- **AI** becomes pervasive as it approaches that of humans



AI Image Generator

Delivering creativity at the speed of your imagination.



“normal” remote work, supply chain crisis, lessened social interaction, IoT, mental health crisis, 5G, mainstream AI, ChatGPT

e.g., “Flying mouse”

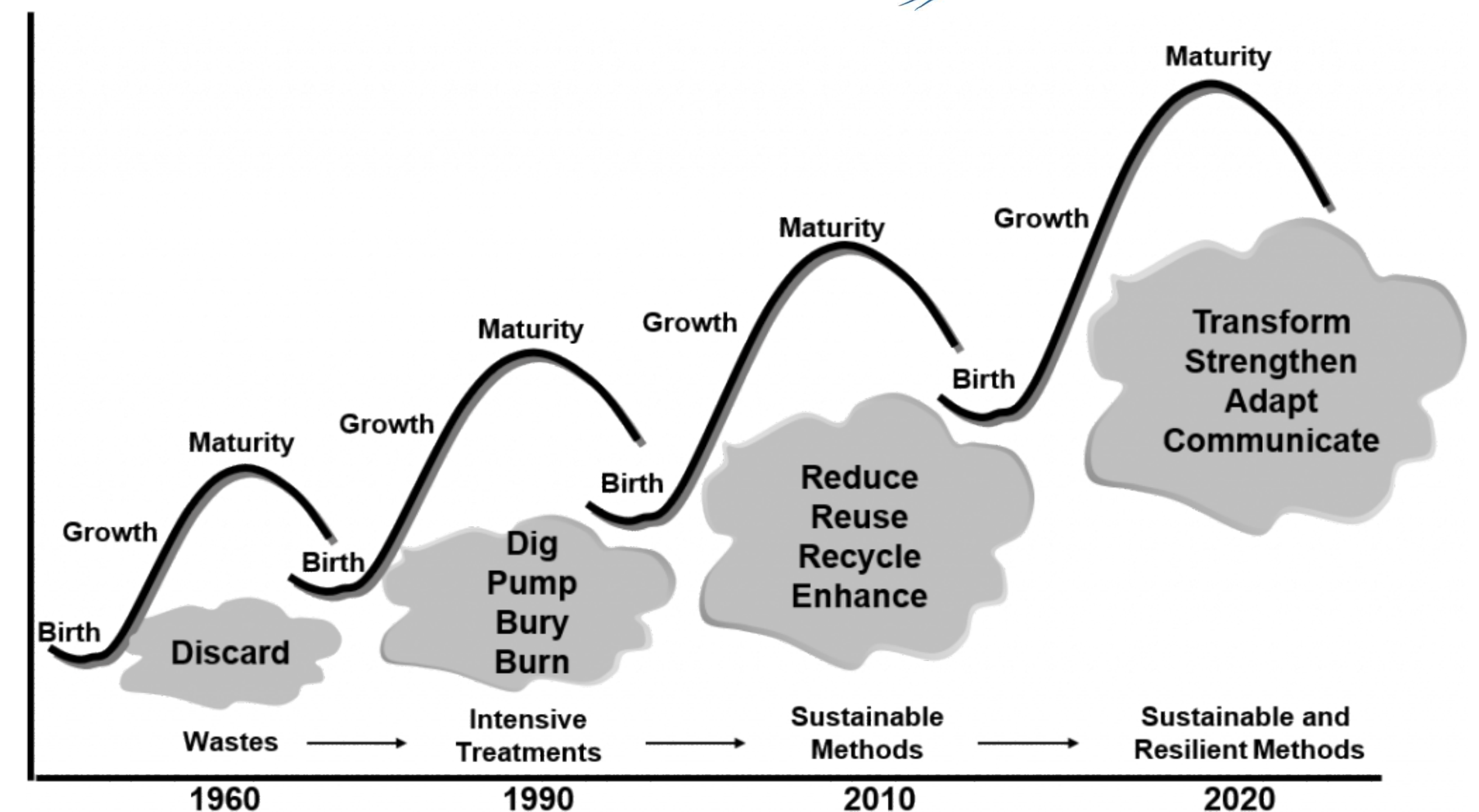
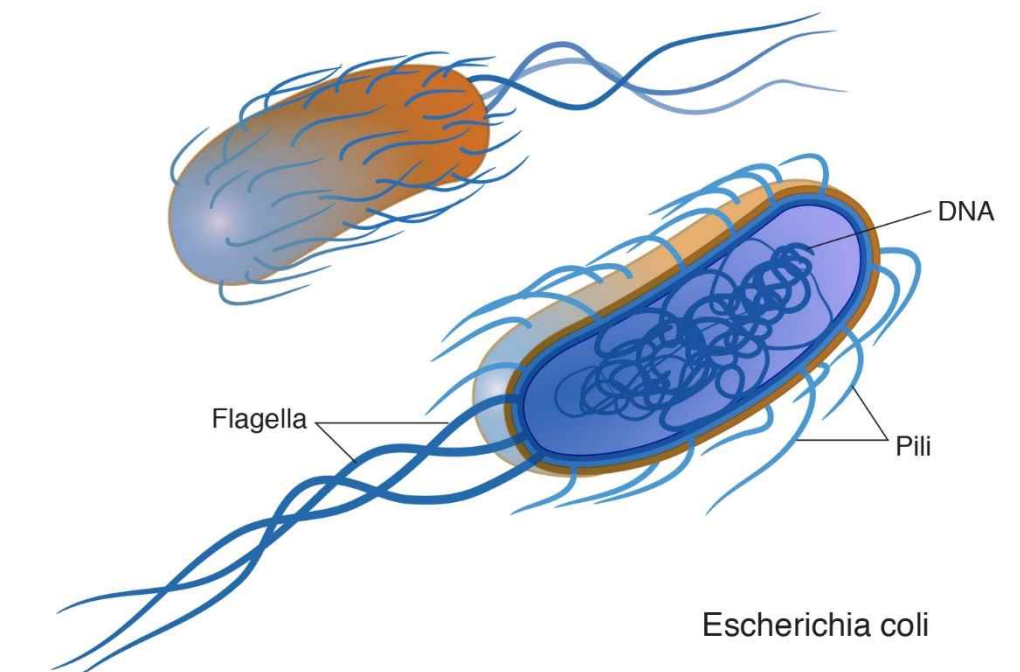


How can I help you today?

2020's Remedial Technologies (in process)



- **All things “Nano”**— nanomaterials, nanowires, nanotubes, nanoswimmers, nanosorbents, nanoparticles, nanobiosurfactants, nanobots?
- **Site-specific biota and formulations** – engineered microorganisms, enzyme addition, manipulation, “menu” technology
- **Biofilms** – (what is old is new again)
- **Increasingly sustainable methods**
-?



The Future

- Isn't Certain
- Isn't bleak
- Will certainly involve a mix of the old and new

WILL:

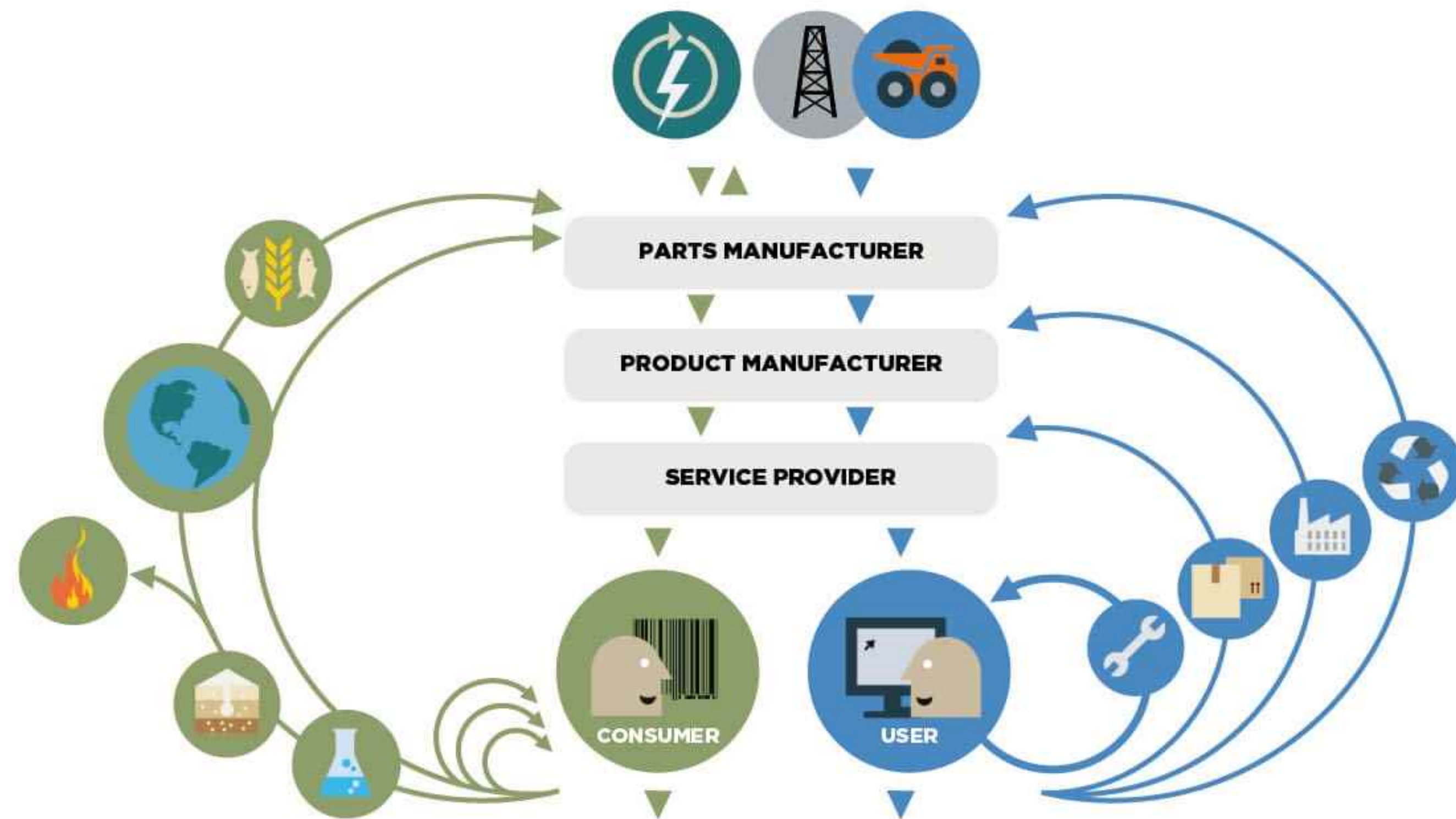
- Be written by new innovators
- Be accepted by "team"
- Encounter unforeseen "chasms" along the way
- Become part of an updated toolbox
- Pave the way for the "next" innovation



What Can You Do?

- Rethink “**Waste**”
- Create the truly “**Circular Economy**”
- **Share** the lessons of the past - failure is the best teacher
- **Provide safety for all** – workers, public, environment

Embrace the changes of new technologies!



Source: Ellen MacArthur Foundation, butterfly diagram

Questions?



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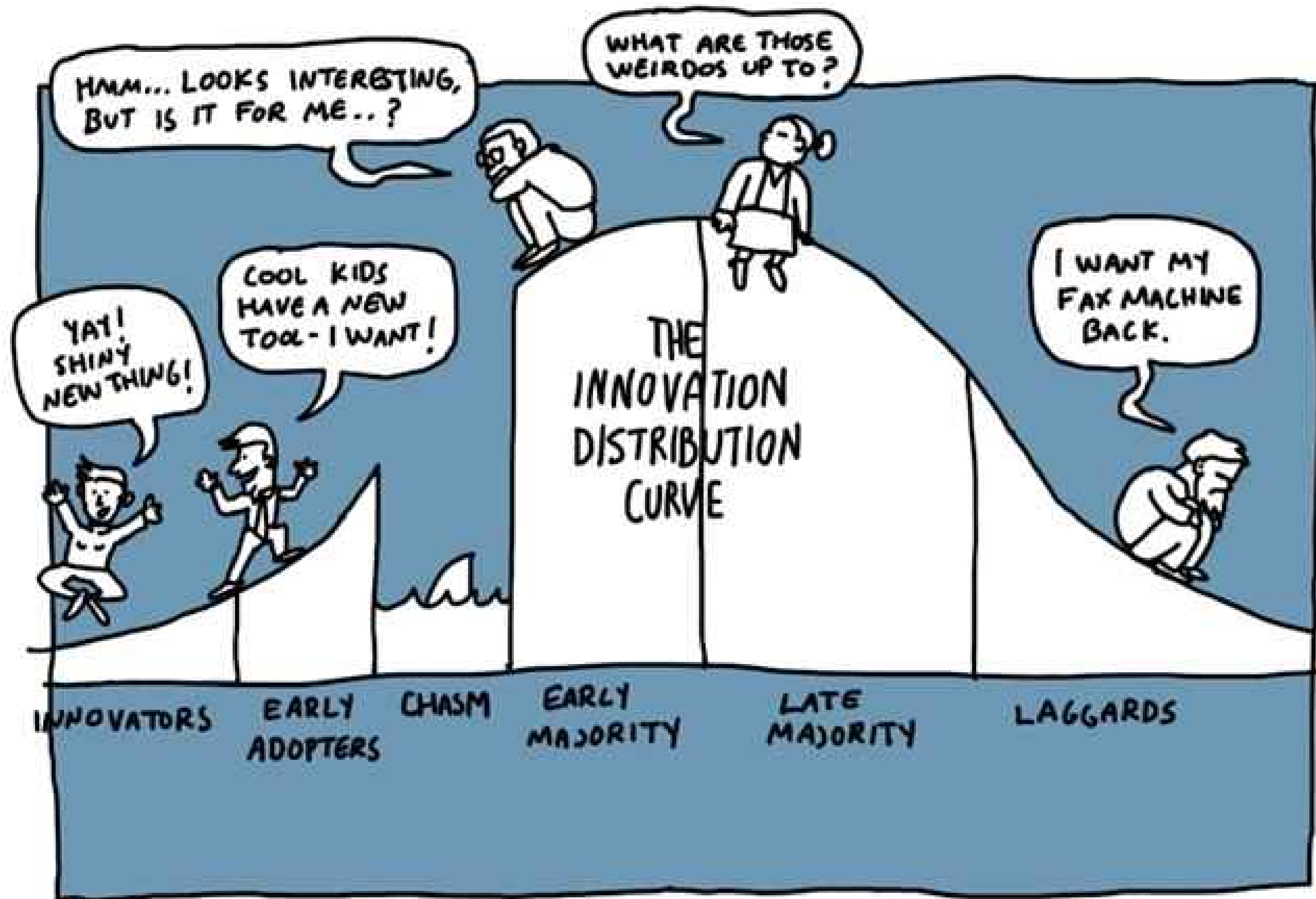


Michael D. Lee, Ph.D.
VP, Research and
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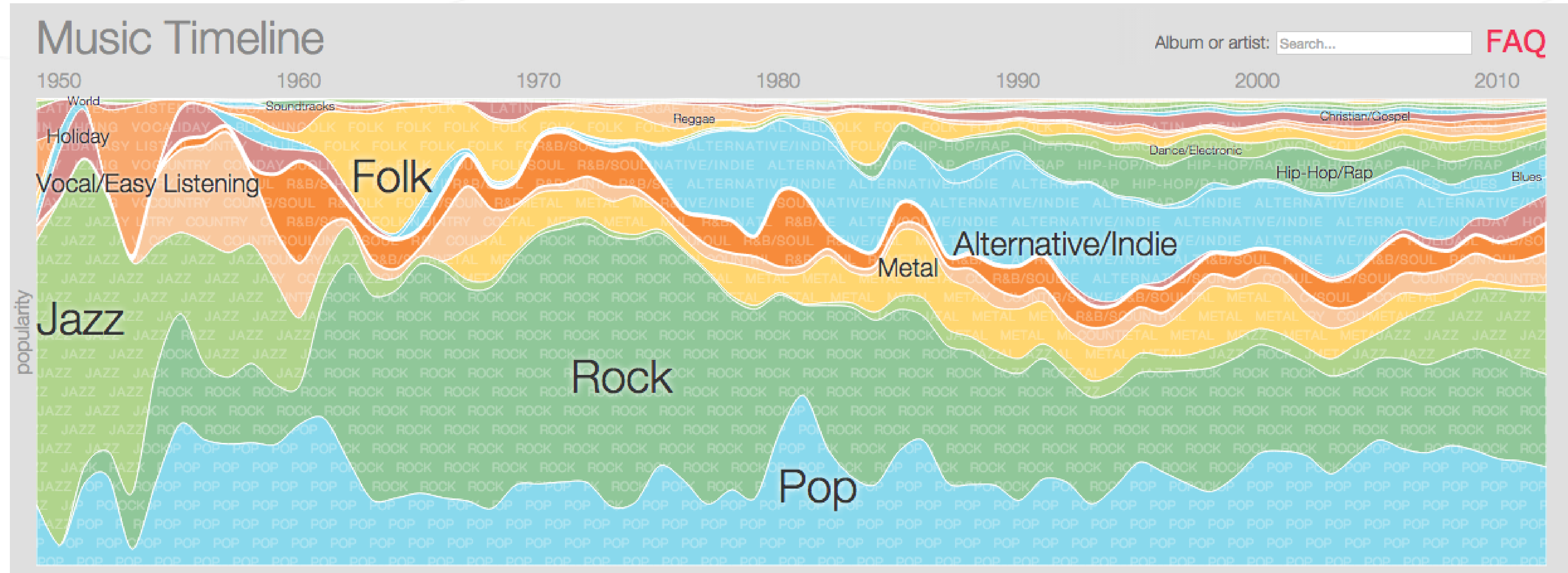
Richard Lewis
President
Lewis Groundwater
Consulting

Adoption Life Cycle (perception dynamics)



Source: Business
Illustrator (2024)

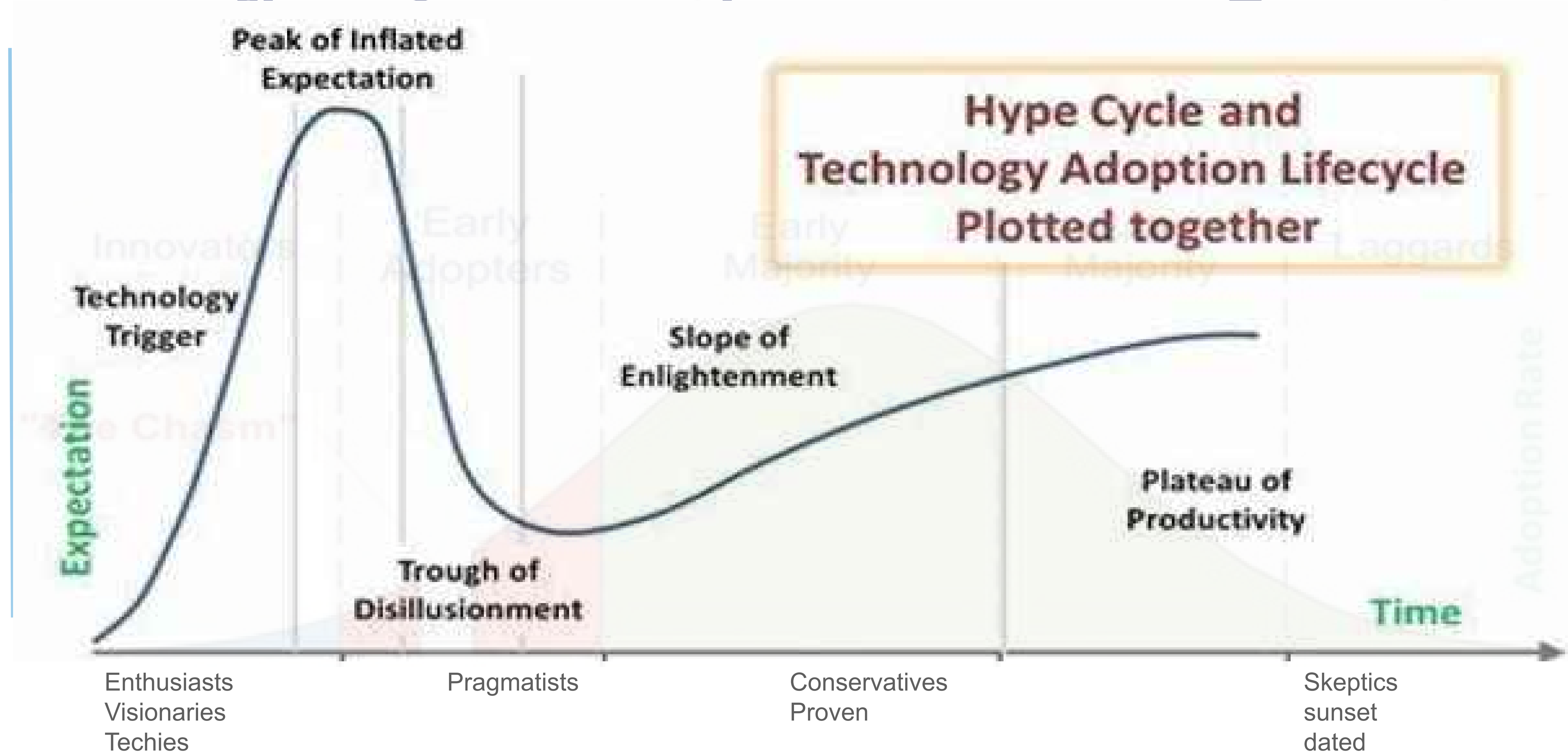
Persistence of Technology (an analogy)



- Technologies never really end
- Some technologies may be fads (limited duration replaced), whereas others persist
- Tastes change over time (what's old is new again)

Source: *Google Music Timeline*
[Music Timeline \(google.com\)](https://www.google.com/music/timeline/)

Technology Adoption (reality)



Regulatory Lag



INCIDENT

- Public outcry
- Action required!!



STATUE

- Law
- Codified



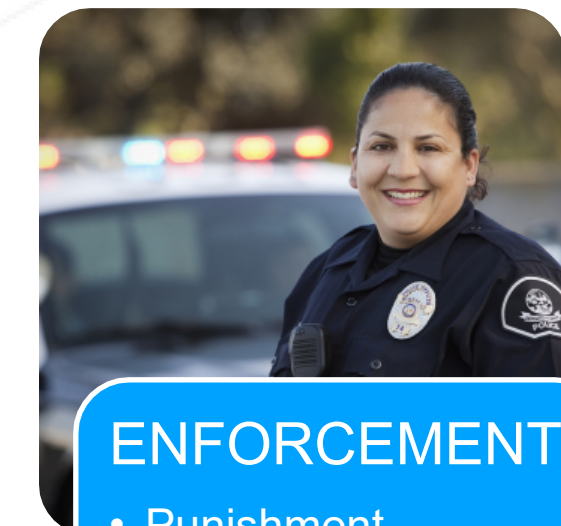
REGULATION

- Responsible body
- Procedures
- Who, what, when, where, why and how



POLICY

- Interpretation
- Clarification



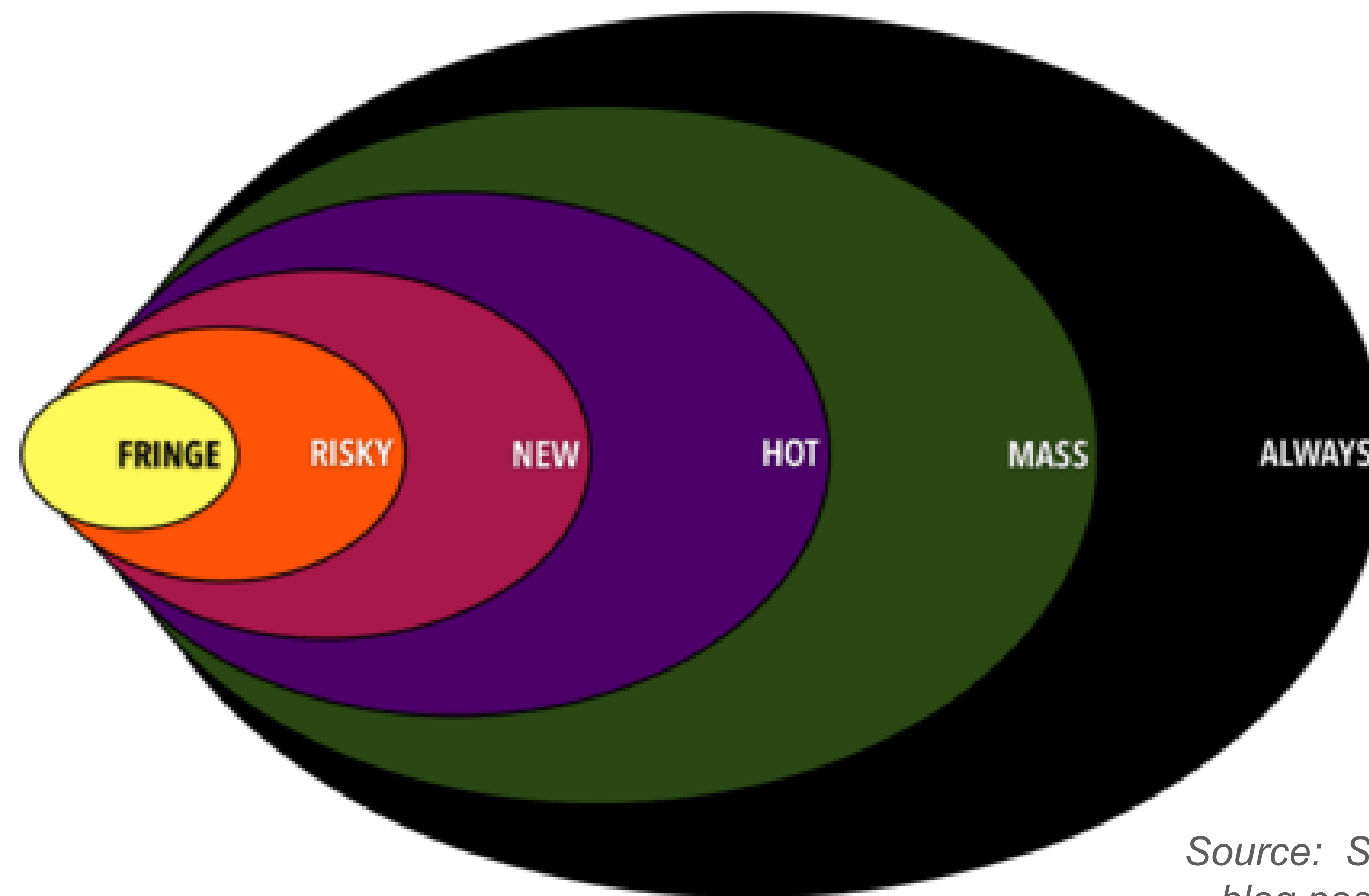
ENFORCEMENT

- Punishment
- Fines, imprisonment, etc.



When does solution occur?

Adoption Life Cycle (alternate view)



Source: Seth Godin,
blog post (2015)