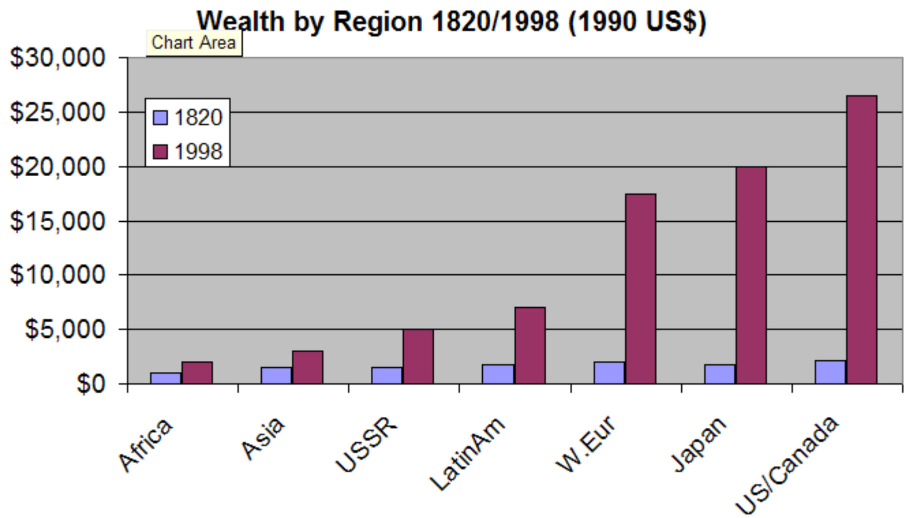
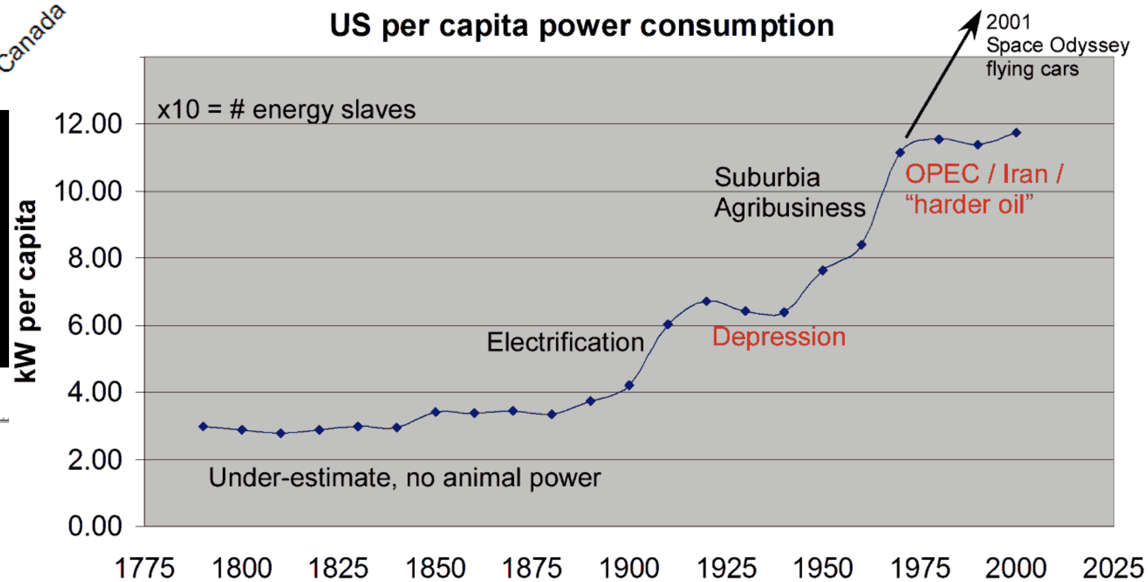
Growth & Decline of Resource Use

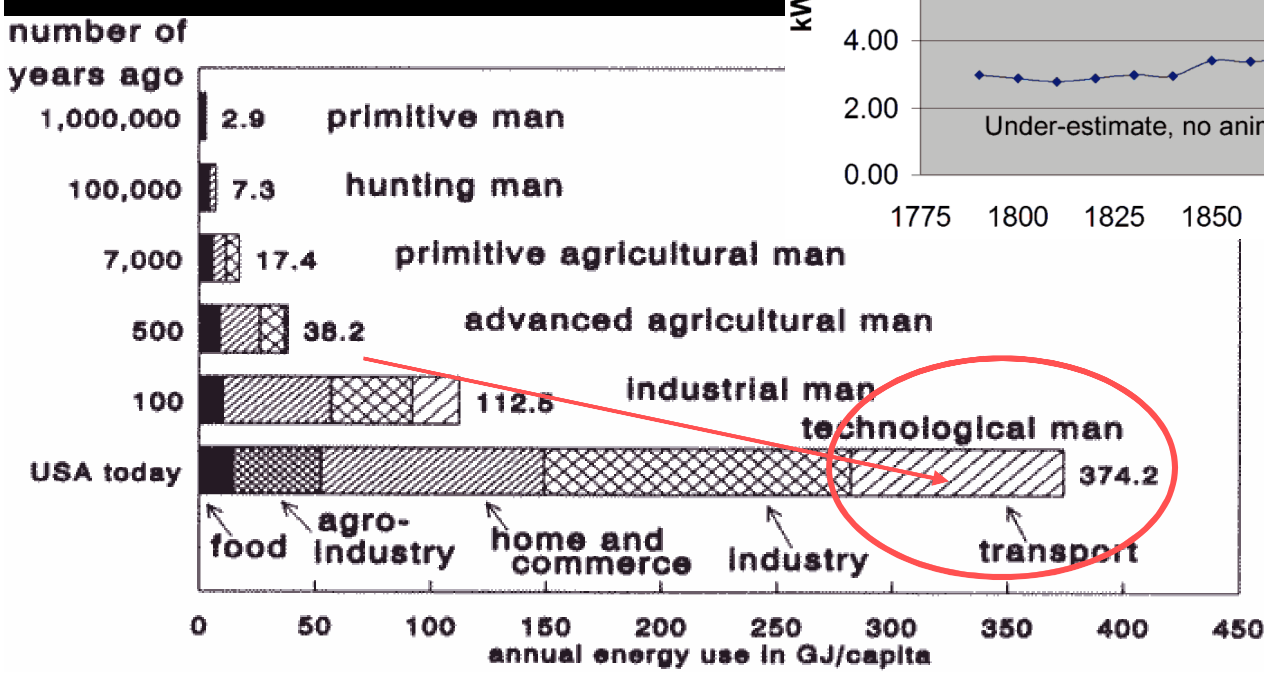
Understanding exponential growth

Exponential vs linear growth
overshoot
stocks vs flows
models

History of per capita energy consumption







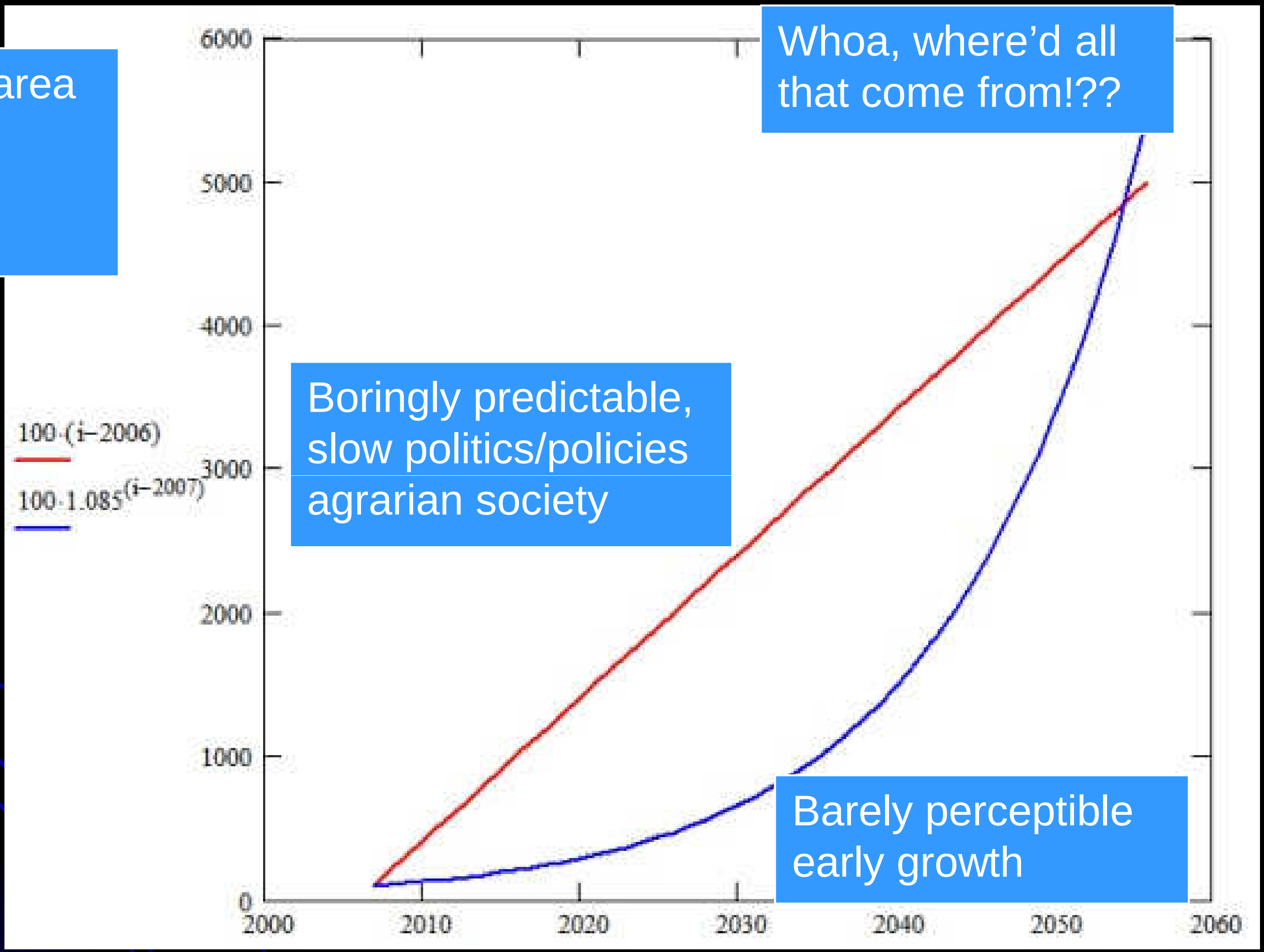
Linear vs exponential growth

- Stuffing mattress = linear growth
  - E.g. $100 / yr x 50 yr = $5,000

- **One** bank deposit + interest = exponential growth
  - e.g. $100 + 50 yrs @ 8.5% / yr gives $5,909 (100×1.085^{50})

Growth compared

Malthus: food area grows linearly, population exponentially

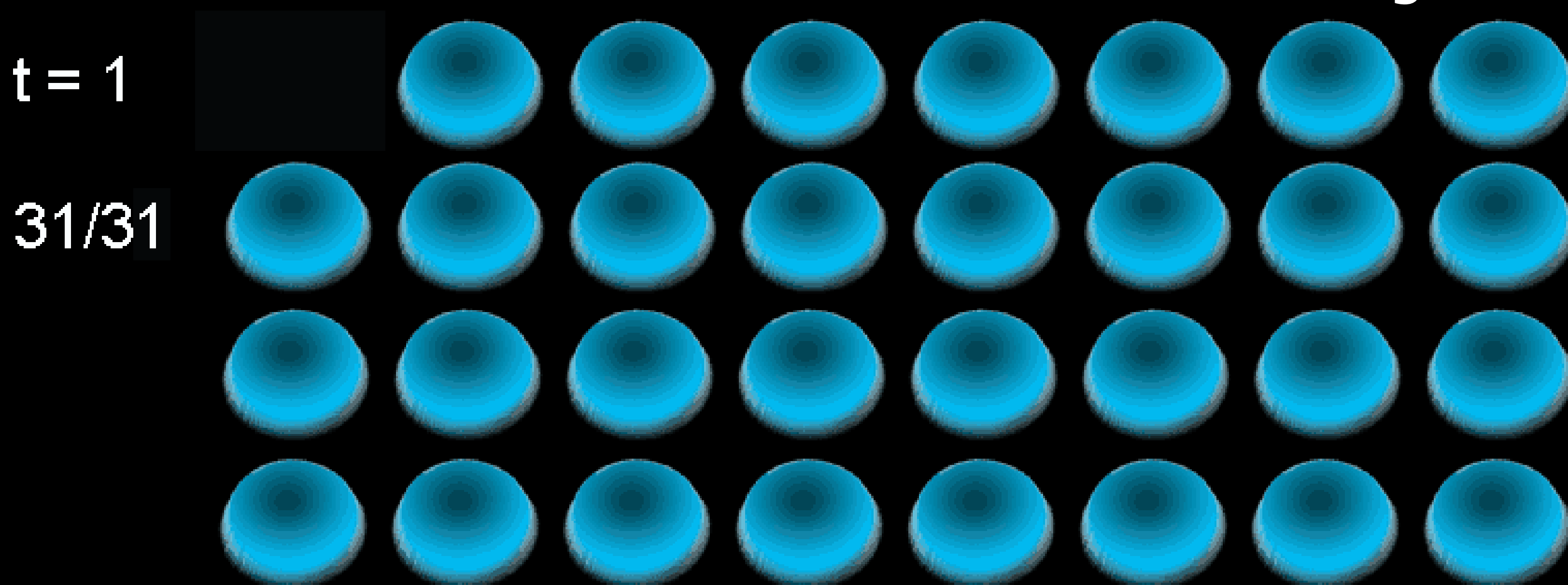


Doubling (halving) time = 70 yr / % annual rate

Economist’s View of Consumptive Growth

Phrase “7% annual growth” → flow rate doubles in 10 yr,
the **Doubling Time**

Let’s see what happens to **non-replenishing** resource (oil)
after each Doubling Time



How many doubling times from end would worries begin?

Surprising implications

Table 1.1: Doubling time & lifetime for given rate of growth at left; longevity of resource at different growth rates at right.

Growth Rate (% annually)	Doubling Time (years)	Resource Lifetime (years)						
0	Infinite	10	30	100	300	1000	3000	10,000
1	70	9.5	26	69	139	240	343	462
2	35	9.1	24	55	97	152	206	265
3	23	8.7	21	46	77	115	150	190
4	18	8.4	20	40	64	93	120	150
5	14	8.1	18	36	56	79	100	124
7	10	7.6	16	30	44	61	77	94
10	7	6.9	14	24	34	46	57	69

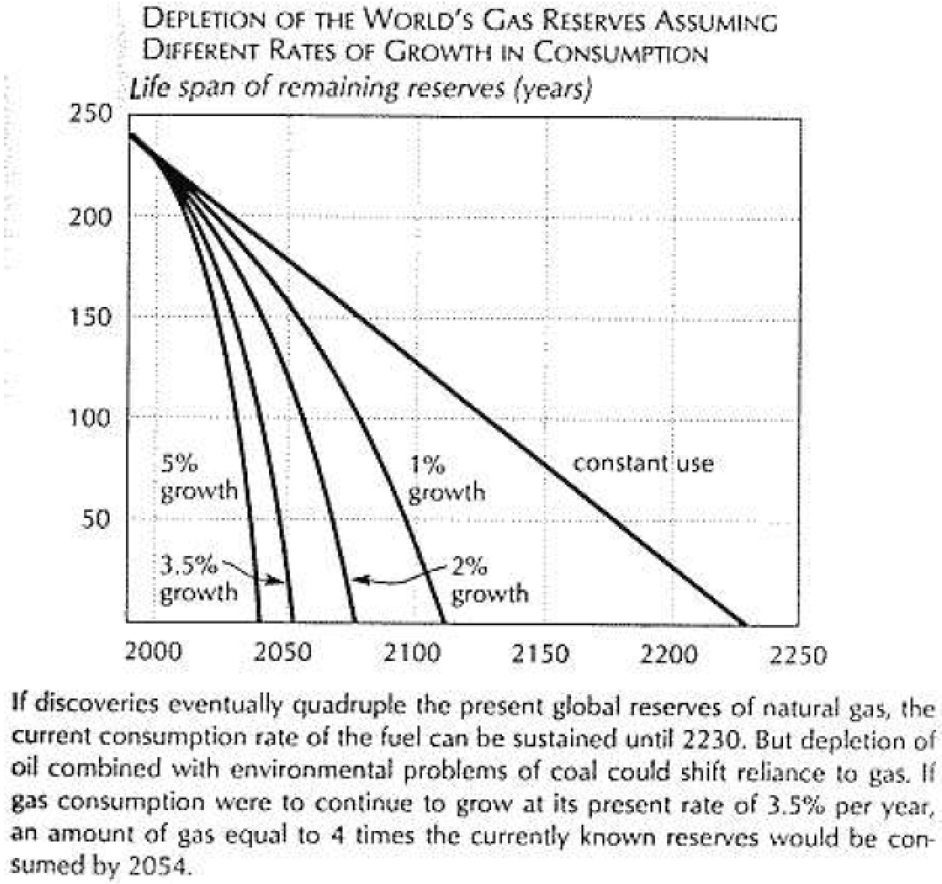
e.g. told that resource will last 300 yr <u>if consumed at present rate</u>

But if our use grows by 5% annually, it will last only 56 yr!

e.g. US coal supply (yikes!)

Oops, wrong … 1000 yrs. Too bad, only 79 yr!

Use more in one doubling time than all before!



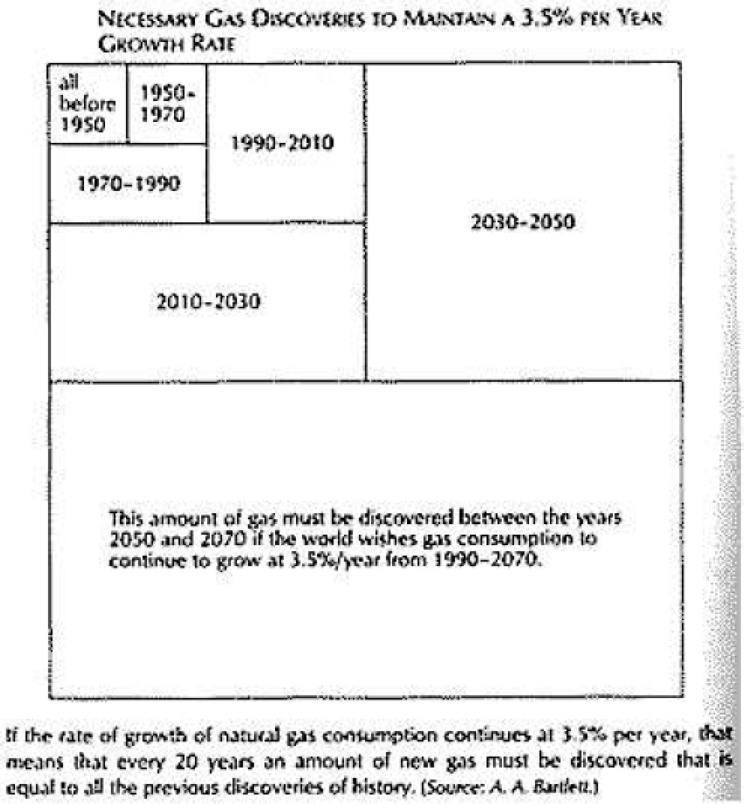


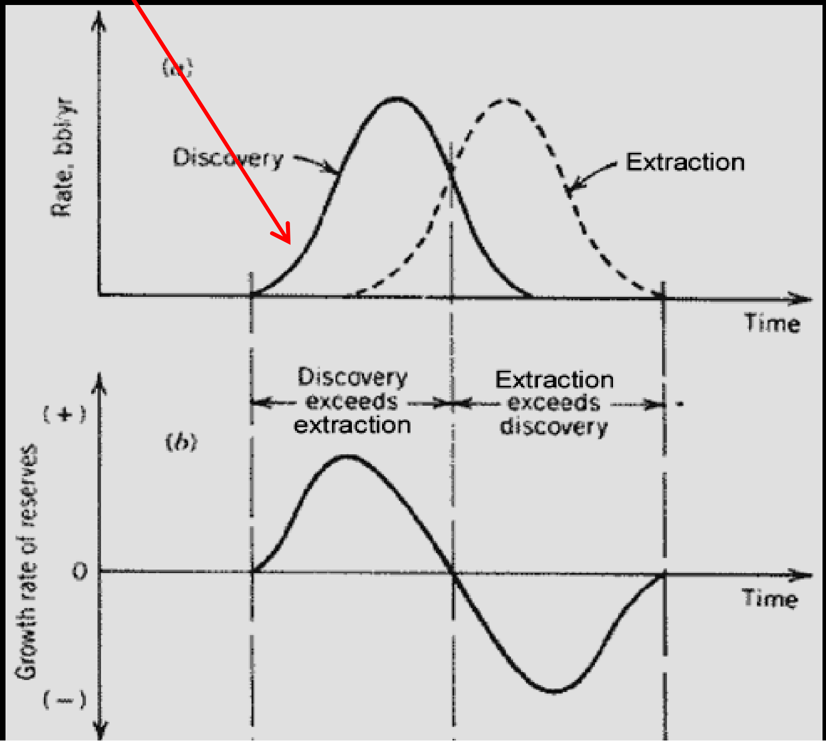
Figure 1.3: Left: Depletion of world natural gas reserves assuming different rates of growing consumption. Right: Necessary discoveries of natural gas to maintain 3.5% annual growth in consumption. Conclusion: *if resource use grows exponentially, the time to exhaust the resource depends only weakly on the initial amount.*

Key points in Resource Use

- Stock = size of bank account, flow = ATM daily withdrawal limit
- Failure to distinguish between stock & flow is one basis of Peak Oil (PO) controversy
  - Media seldom get it right
- Critics say: we are not running out of oil ! (stocks)
- Peak Oilers AGREE! But say "flow rate of oil can no longer increase"
  - bank account size is irrelevant
  - Focus should be on "how do rates change over time?" …

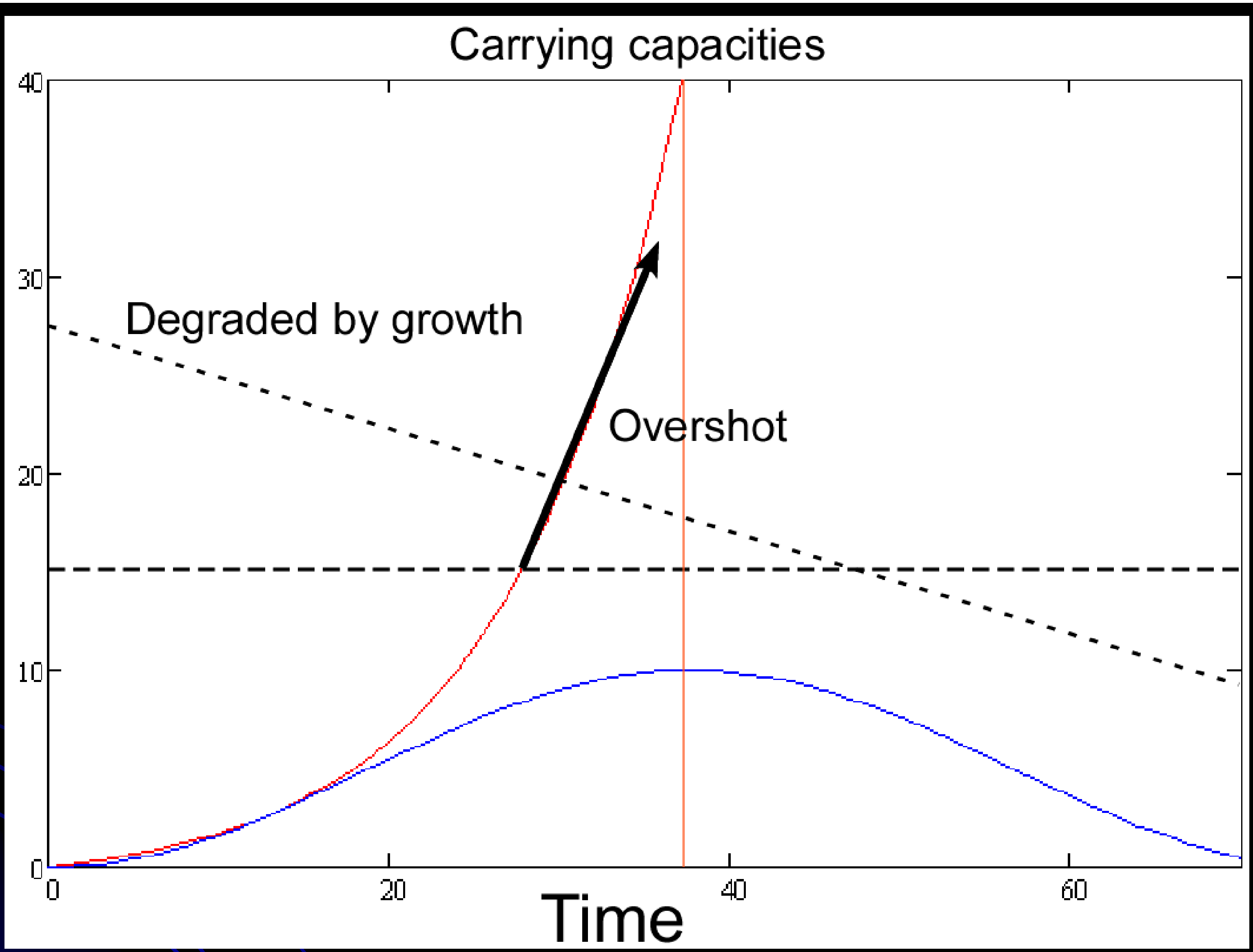
Discovery rate & burn rate

- "**logistical problems**" inhibit discoveries
  - Initially economic, eventually geological
  - These quickly end exponential growth!
- Discovery rate peakS, is FLAT, then declines
  - Peak signals urgent need to find new supply/fuel
  - Predicts future extraction peak (Hubbert peak)
- Extraction peak signals imminent crisis



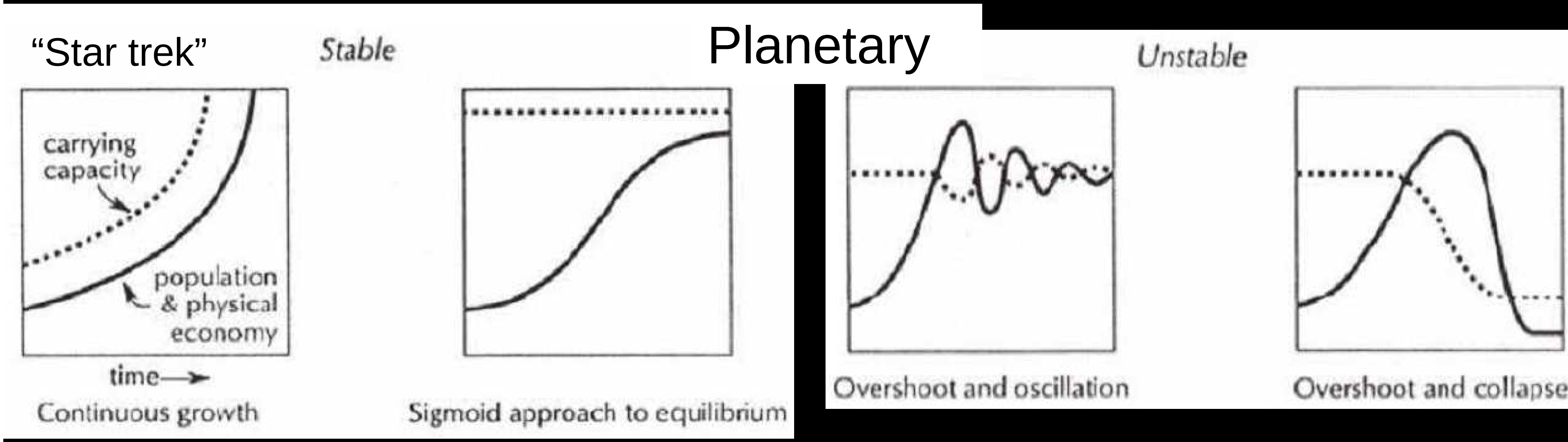
Overshoot

- Ecology concept: carrying capacity (CC) = sustainable population of region
  - Below CC : pop. can increase sustainably
  - Exceed CC : eventually pop. (& CC) decreases
  - Fraction of CC : ecological footprint (how many "Earths" needed to support humanity at our level? www.ecologicalfootprint.com
- CC can increase if exploit new resources
  - Wood → coal → oil → ~~uranium~~, world pop. in 1650 (0.6 billion) → 1900 (1.6 b) → 2010 (6.9 b)
  - But waste from new resources can reduce CC



Outcome depends entirely on the specific dynamics of growth Patterns are …

Attaining / Overshooting CC



- Growth has momentum, sails past limits
- Which outcome depends on strength & timing of feedbacks that counter growth
- What feedbacks would stop growth?
  - Initial concerns were of chemical pollutants

Discovering chemical pollutants

- LA smog from automobiles 1943
  - catalytic converter 1975
- London UK smog from coal heating Dec 1952, killed 12,000 people
- Silent Spring (R. Carson) 1962
  - DDT banned 1972
- Global climate change mid-1960s
- Santa Barbara, CA oil spill 1969
- Love Canal, Buffalo NY 1978
- Ozone hole 1985
  - CFC phase-out started 1987
- Chernobyl (& Three-mile Island) nuke accidents 1986 (79)
- Abrupt climate change mid-1990s CO_2

Late 1950's

- Govt studies : review oil supplies
  - US oil diminished to win World War 2
  - USSR (Siberia): significant oil mostly untapped
  - Lip service: others will want to industrialize
  - GM & Ford pushed internal combustion engine, bought & dismantled electric trolley systems to force cities to buses
- Resources for Future (Rockefeller Found.) infinite atomic power = infinite economic power
  - Harrison Brown: will deliver unlimited resources
  - Rapid expansion of nuclear power 1973+
  - Handled electricity but not US transportation

Early 1960s

- Hardin: Tragedy of the Commons
- Ehrlichs: The Population Bomb
- Pimentel & Odum: quantified energy inputs in agriculture

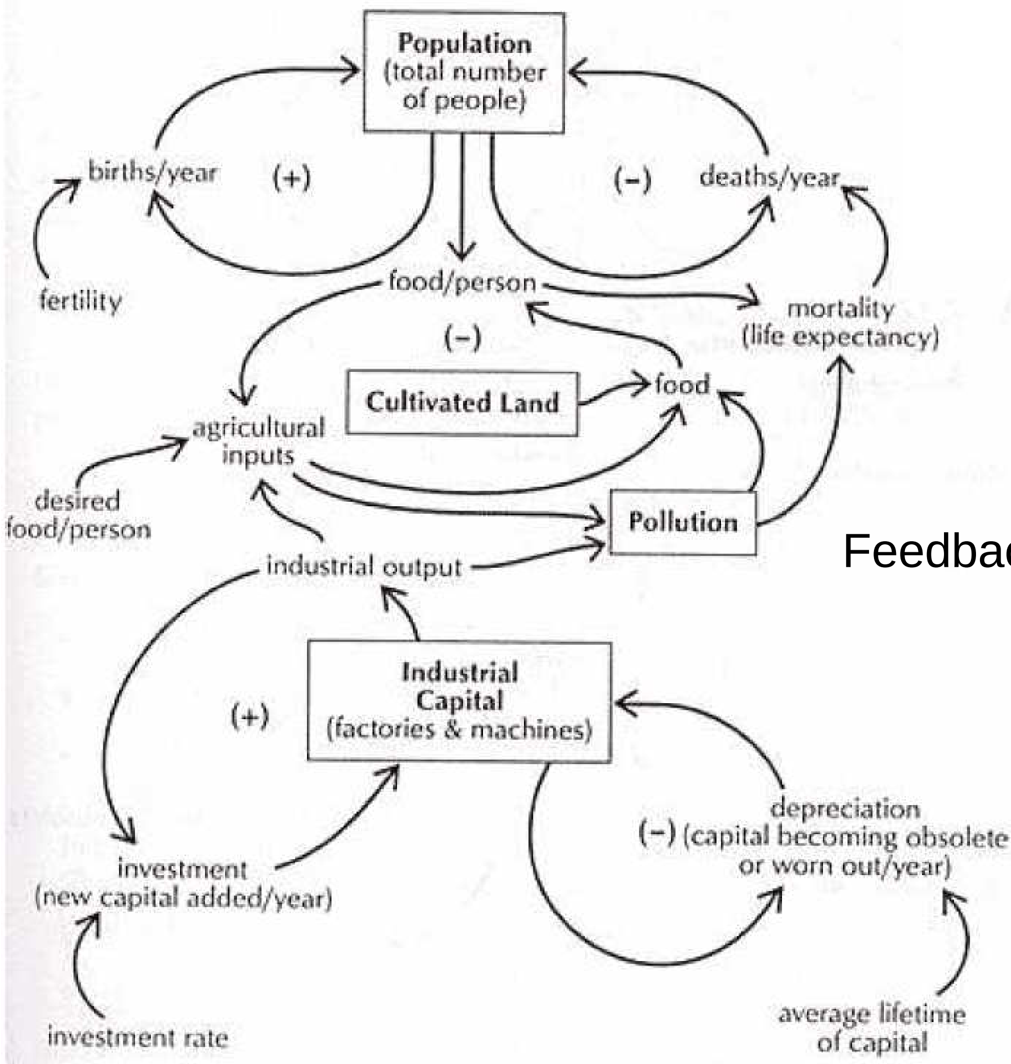
Late 1960s

- <u>Club of Rome</u>
  - Businessmen: how does pop. growth modify environment by pollution & resource exhaustion?
    - Topics ignored by economists (“externalities”)
    - What impact on food, environment?
  - Solicited MIT computer study 1970-2
- To stimulate discussion: Limits of Growth 1972
    - Backlash from “growth community” bankers/economists
    - “Oil shocks” shortly thereafter lent apparent support
      - Pres. Carter warned of exp. Growth & ME control of US
      - Lost re-election to Reagan even after “Carter Doctrine”
  - Most assumed LoG was invalidated after ME supply was restored (big US oil imports & ME militarization including Israeli nuclear weapons)

[redacted]

Start of Systems Dynamics

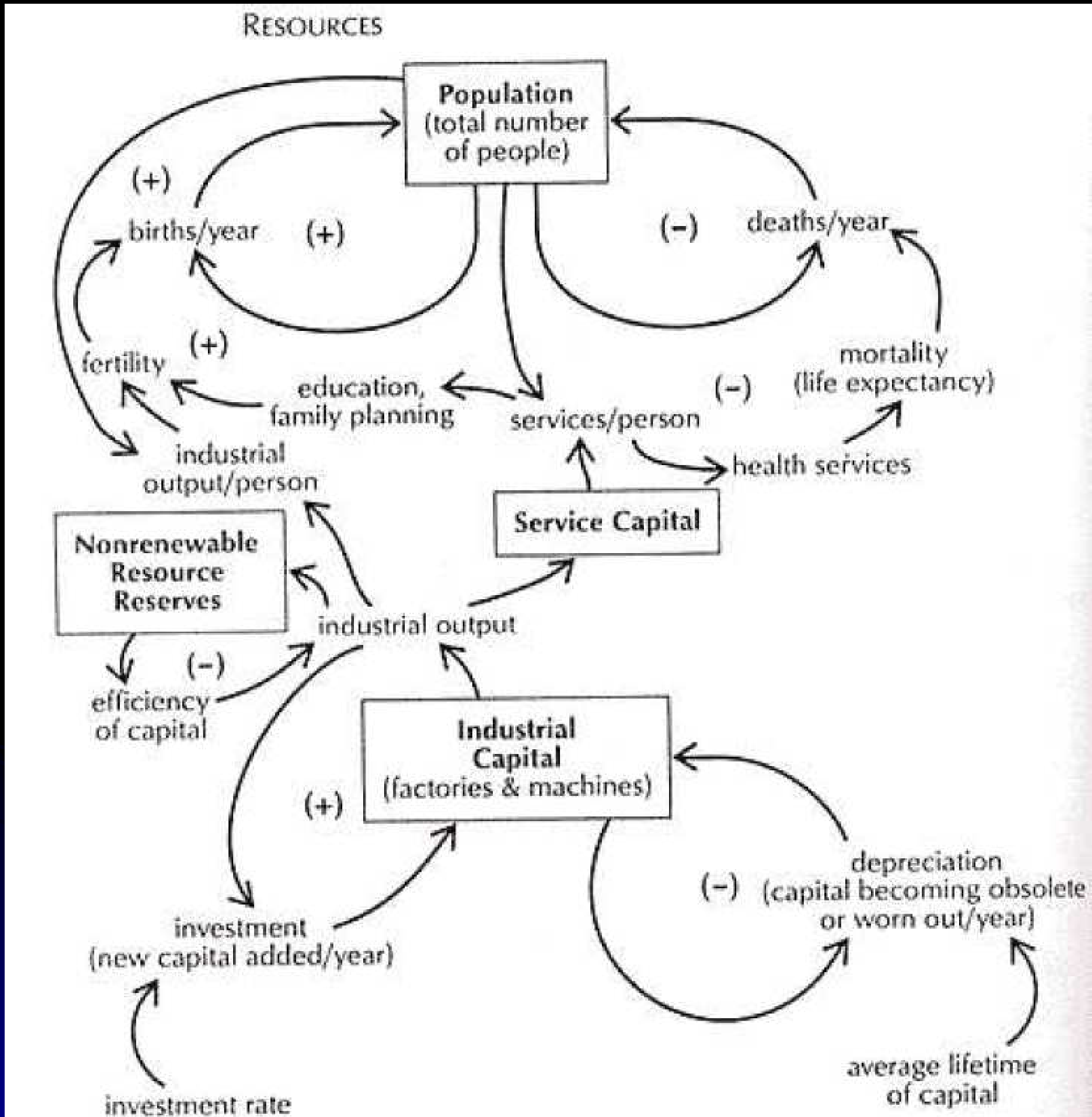
- Model exponential & linear interactions
- Rediscovered overshoot dynamics evident in animal populations



Feedback loops

[redacted]

Feedback Loops for Population, Capital, Agriculture, & Pollution [Beyond the Limits]



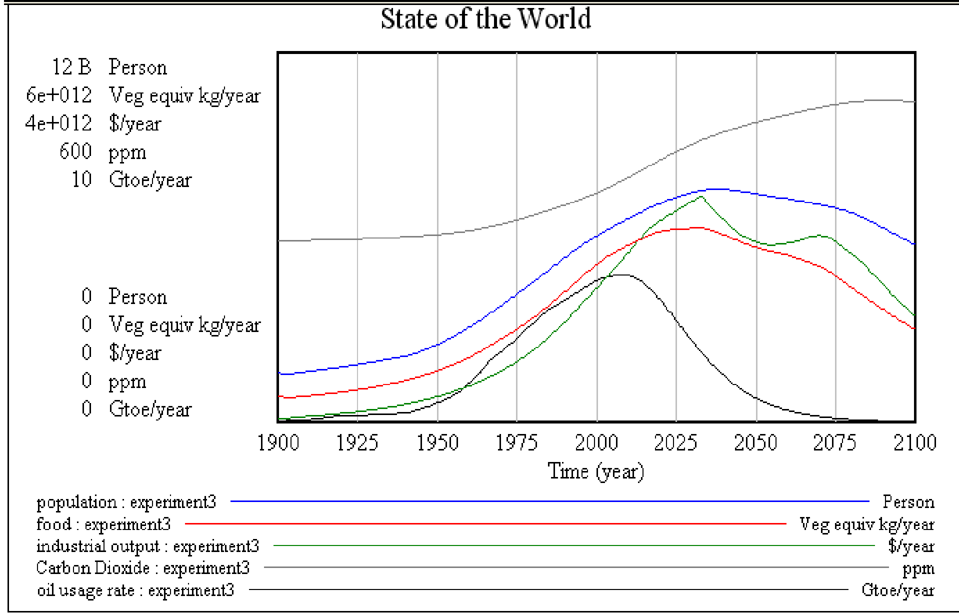
Feedback Loops for Population, Capital, Services, & Resources [Beyond the Limits]

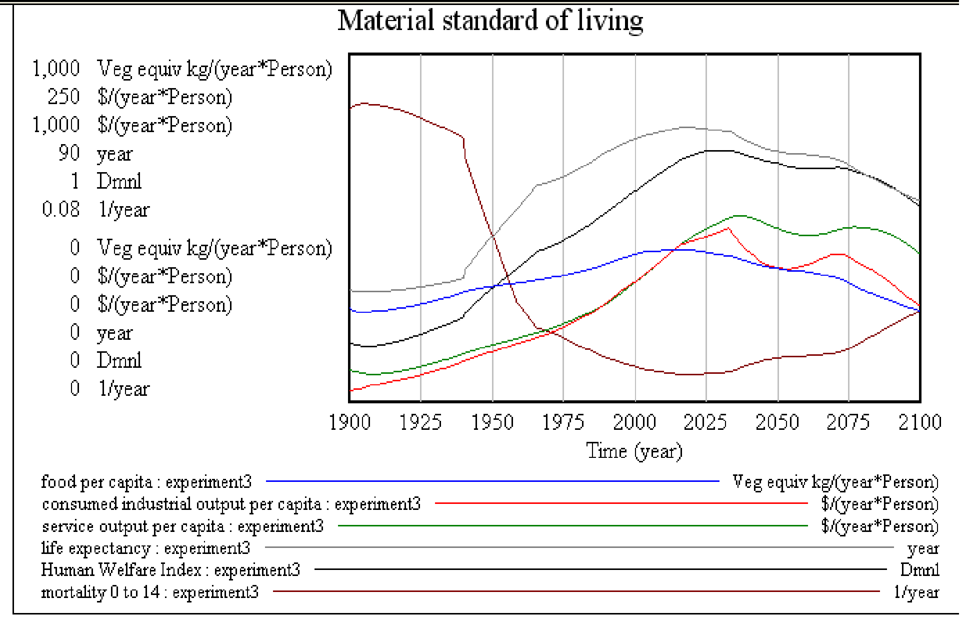
Obviously,
highly simplified!

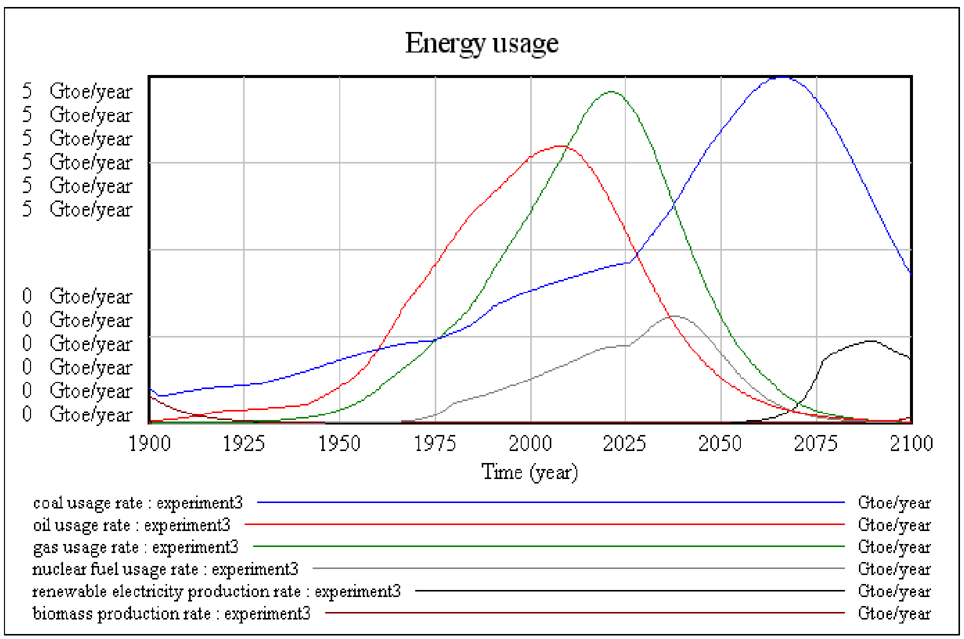
Evolving studies of Limits of Growth

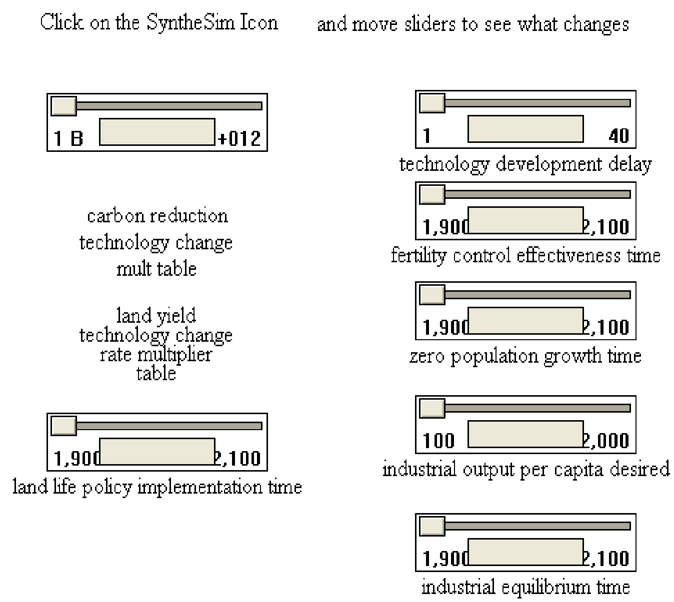
- Note: LoG has been completely dismissed by mainstream (1980 Ehrlich/Simon bet)
- World3-03 (1991, 2003)
  - no distinction between different energy forms or regions -> worldwide collapse evident by ~2030
- New World (2009)… let's run it!
  - distinguishes renewable / depleting energy forms -> transition to new forms only as old are overwhelmed by constraints (oil soon, NR+coal much later)

Explore World3 & New World3



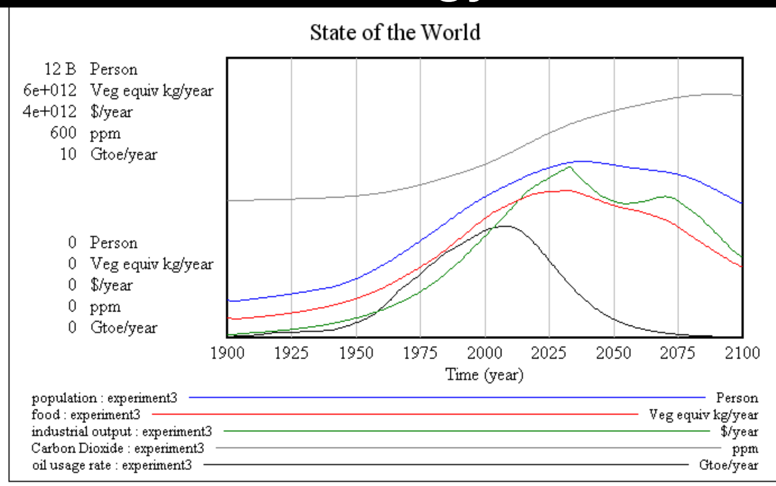


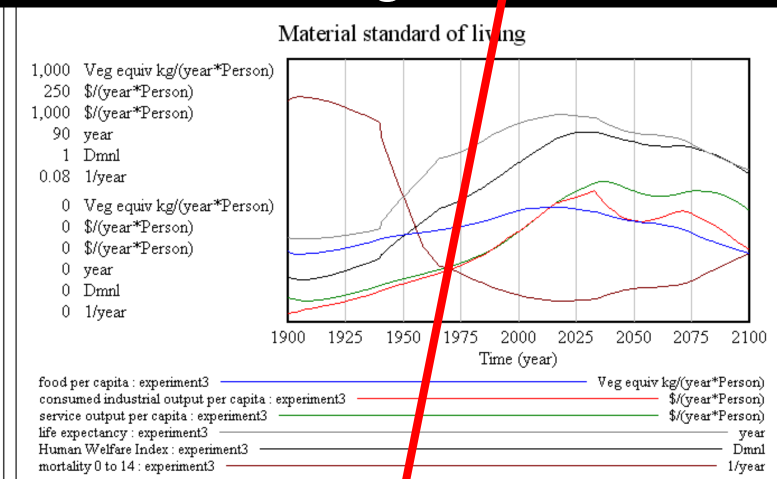


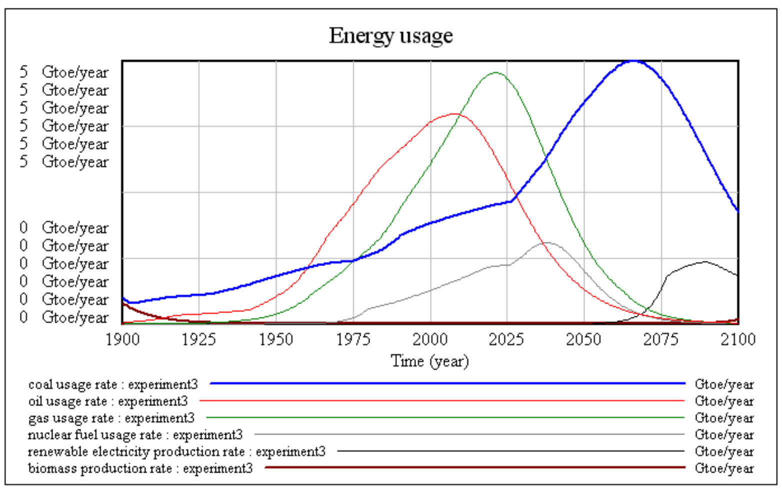


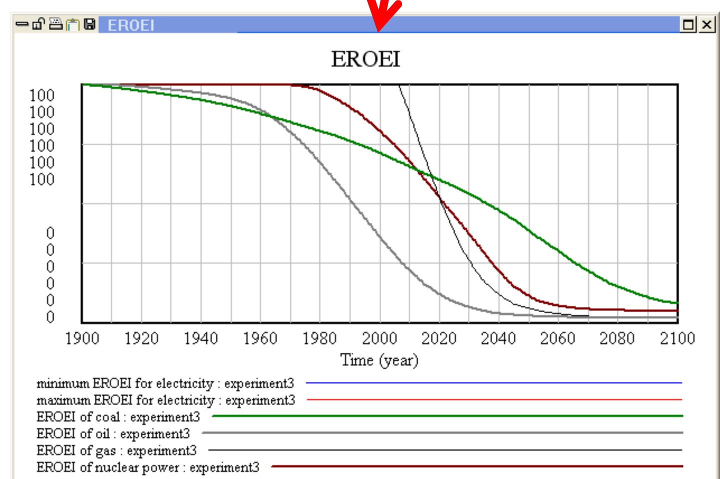
Energy Return On Investment

- Energy must be used to generate energy
  - E.g. energy embodied in an off-shore drilling rig
  - Reduces net energy available for other things



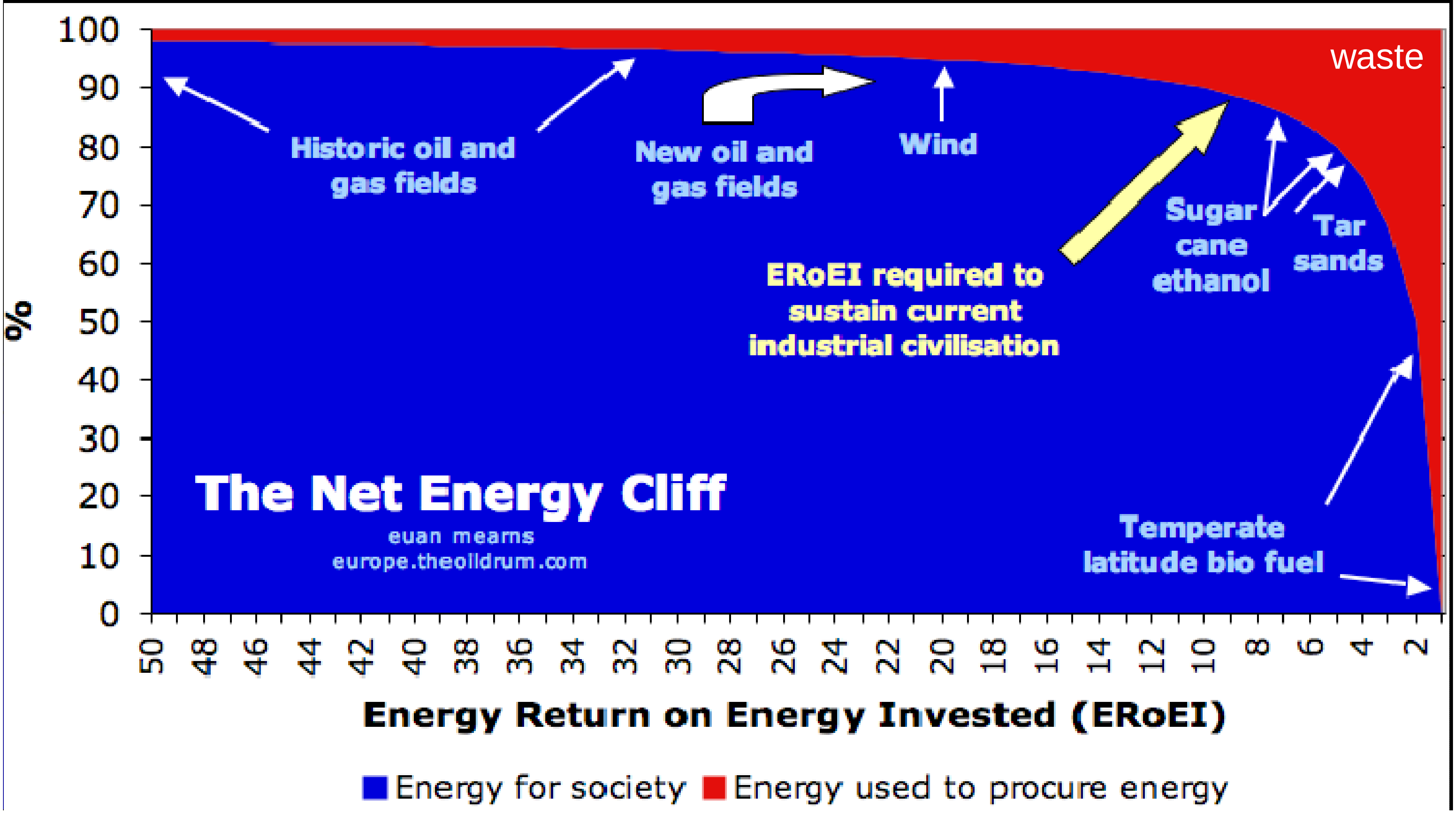






Energy Return

Currently, a minor impact on efficiency compared to engineering



Energy conversions

In practice

Recall : 1st Law Thermodynamics

$$Q = \Delta U + W$$

Heat engine

Heat In →

Change of
Internal energy
(T rise and/or
phase change)

+

Mechanical
work done

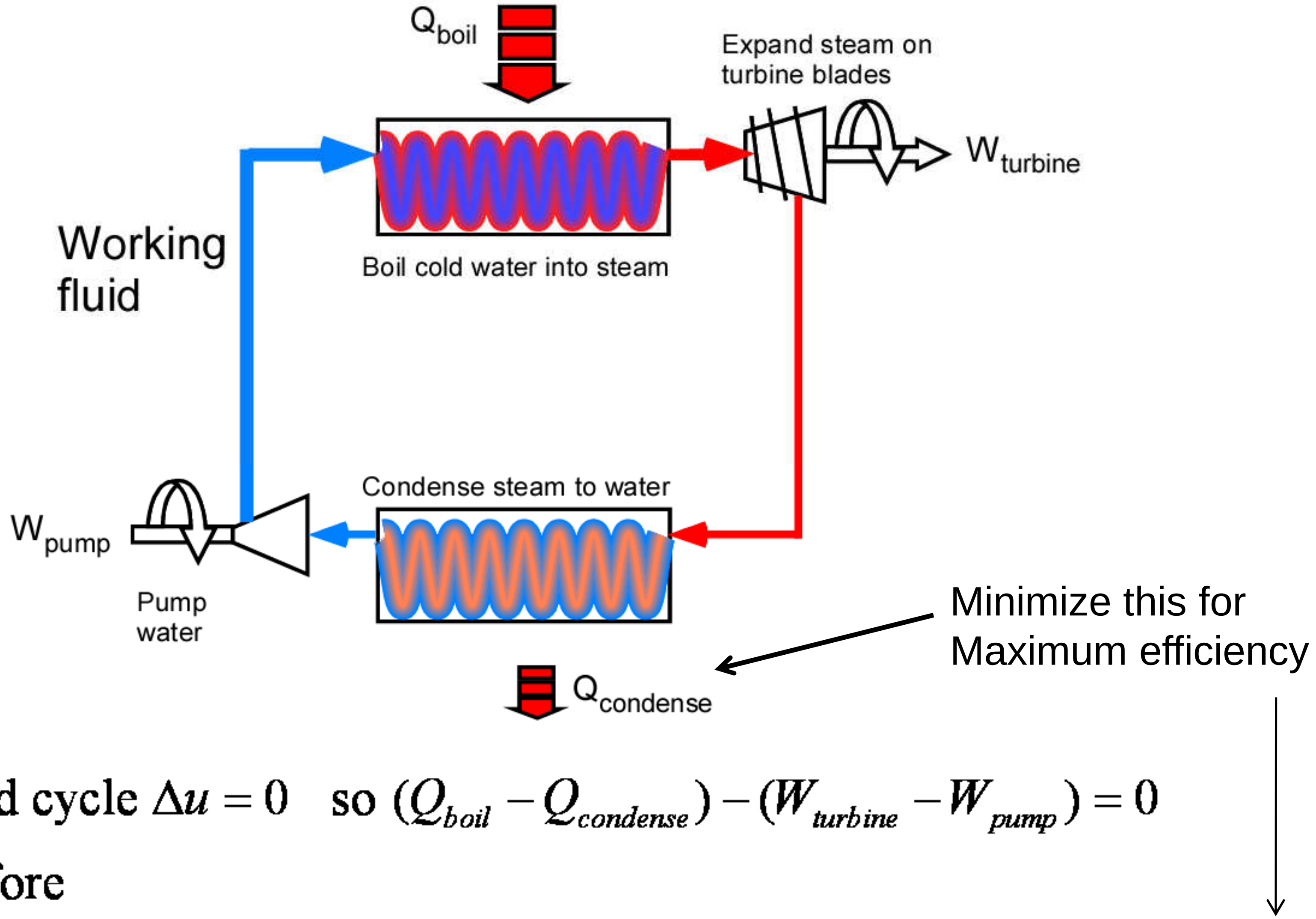
Q

ΔU

W

- Burn fuel : chemical -> heat energy
- Working fluid (e.g. water) flowing hot -> cold region does mechanical work

Closed cycle steam plant



$$\text{Around cycle } \Delta u = 0 \quad \text{so } (Q_{boil} - Q_{condense}) - (W_{turbine} - W_{pump}) = 0$$

Therefore

$$\text{efficiency} = \frac{\text{net work out}}{\text{heat input}} = \frac{W_{turbine} - W_{pump}}{Q_{boil}} = \frac{Q_{boil} - Q_{condense}}{Q_{boil}} = 1 - \frac{Q_{condense}}{Q_{boil}}$$

2nd Law Thermodynamics

- No cycle converts all heat in -> same work out
- Why? Heat disorders working fluid.
  - Energy into molecular disorder is entropy (remainder into work is exergy)
    - e.g. water -> steam, molecules more mobile
    - Unit is J/K, entropy increases with T
  - Disorder is reduced in working fluid as steam condenses to water, but resulting heat $Q_{condense}$ is released into environment
  - Hence, efficiency = $1 – Q_{condense} / Q_{boil} < 1$

- Most efficient work from burning fuel is (Carnot)

$$\varepsilon_{max} = \text{(Max work out / Energy in)} = (T_H - T_L)/T_H = 1 - T_L/T_H$$

T_H and T_L are working fluid temps in K

Burning fuel CANNOT BEAT this limit

e.g. wood stove $T_H = 300^oC + 273 = 573K$

exhausts to $5^oC + 273 = 278K$

so max efficiency = 1 – 278 / 573 = 0.51 = 51%

Min of 49% of input energy is wasted, the entropy

“90% efficient” stove converts 0.9·0.51 = 46% wood chemical energy into heat , 54% into waste

Waste (entropy) streams

Enter environment as

- Combustion products (gases, liquids, soot, ash)
- Radioactivity (from coal ash, nuclear waste)
- Frictional heat

Can tap cascade to T_L at each stage & reprocess

- To reduce waste volume
- To extract useful heat (co-generation)
  - e.g. UNC coal plant :
  - high pressure steam for hospitals, lower for food service, lowest for building/water heat including dorms

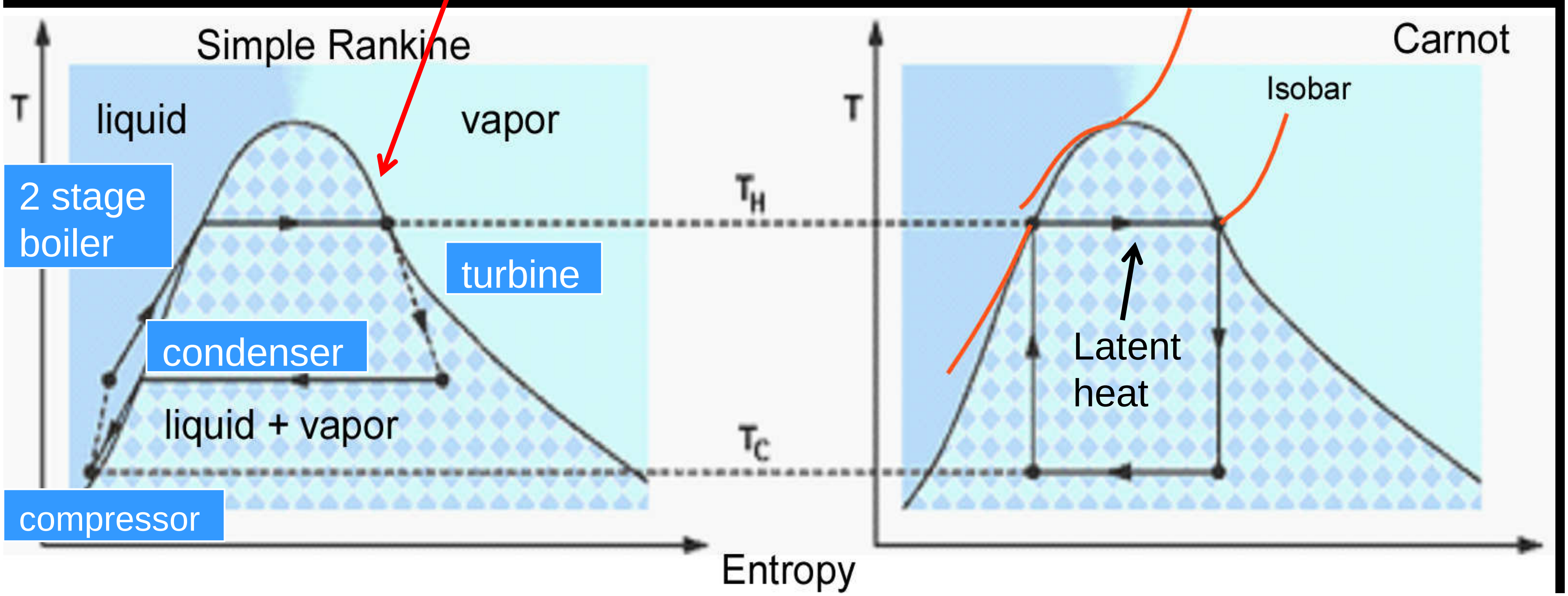
Engineering is dumping entropy in clever ways

Maximum (Carnot) Efficiency

Carnot requires T_H constant, but real working fluid attains this only on isobar in its liquid+vapor state

- Its phase curve limits T_H

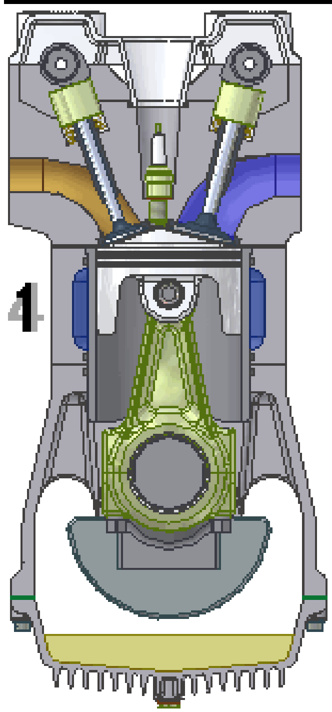
- Material stress (softten at T_H , typical turbine 565℃)
- Environment (at T_L , typical 30℃)

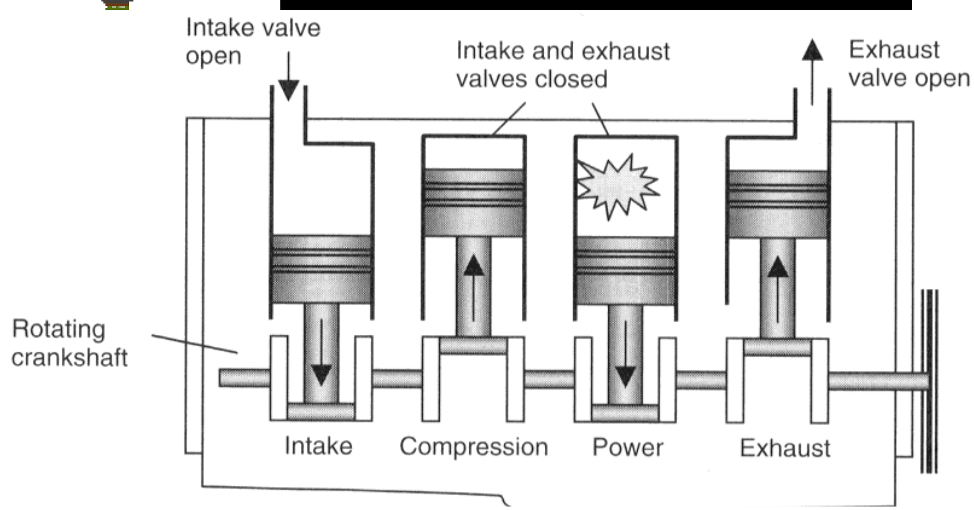


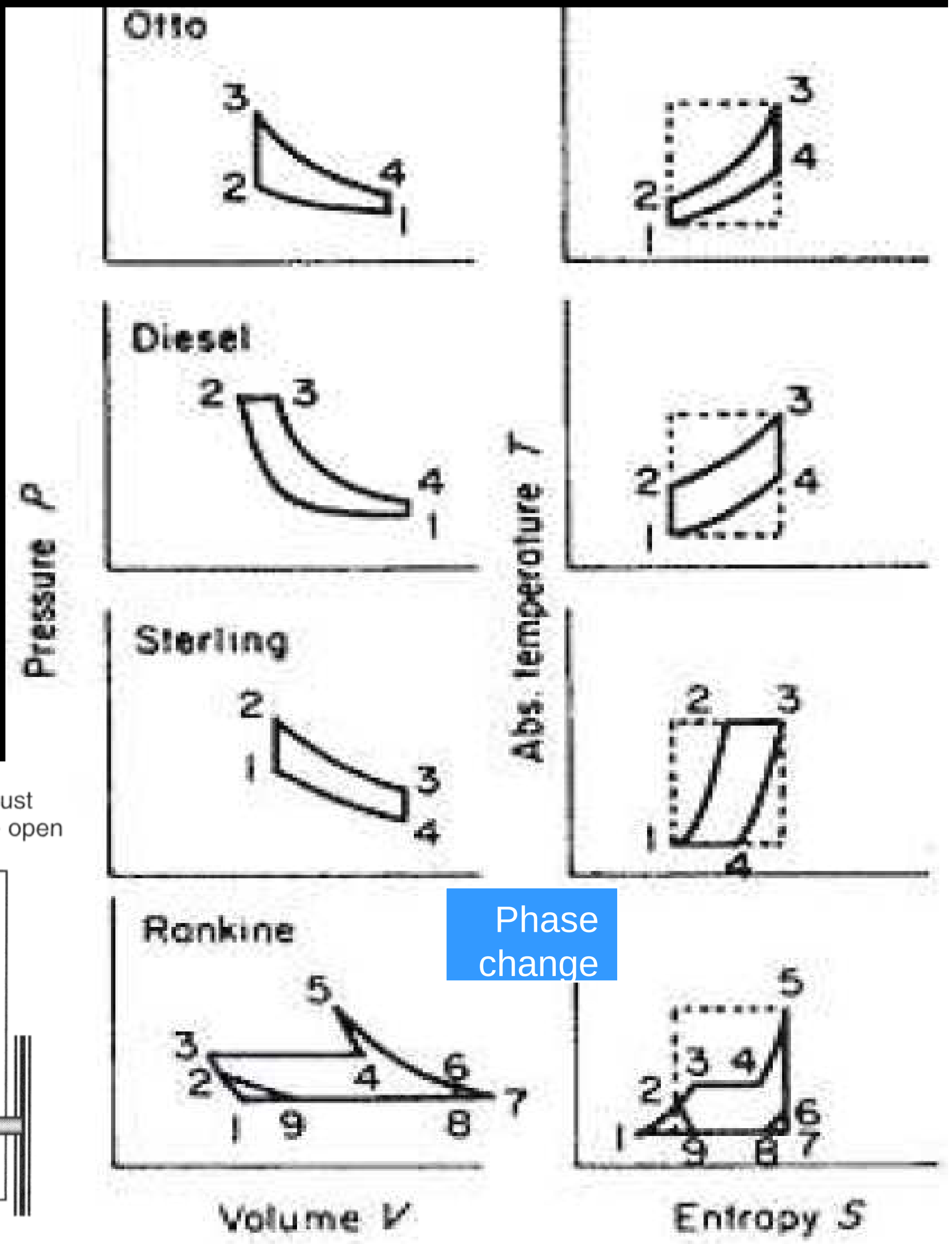
Practical engine cycles 1-4

Square box is Carnot. Others are less efficient by fraction solid/dotted areas.

Faster cycle = more power out "cut corners" so reducing efficiency







Power & efficiency are opposites!

Internal Combustion Engine

A powerful ICE must get poorer gas mileage

Many simulated engine cycles

Energy Conversions

- Low (directional motion) -> high (random) entropy are efficient & vice versa

Table 2.5: Energy conversion devices and their efficiencies.

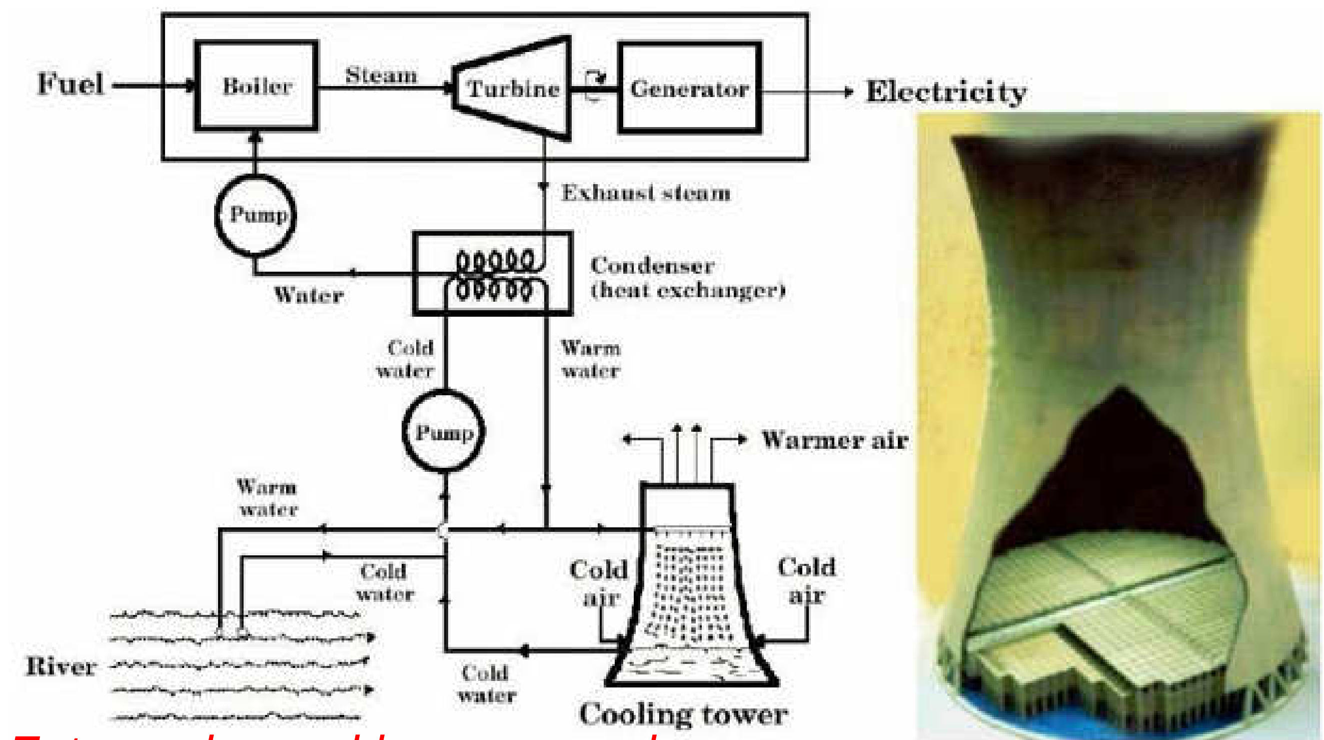
Conversion device	Energy input	Useful energy output	Efficiency %
Electric heater	Electricity	Thermal	100
Hair drier	Electricity	Thermal	100
Electric generator	Mechanical	Electricity	95
Electric motor (large)	Electricity	Mechanical	90
Battery	Chemical	Electricity	90
Steam boiler (powerplant)	Chemical	Thermal	85
Home furnace (Gas / Oil / Coal)	Chemical	Thermal	85 / 65 / 55
Steam turbine (powerplant)	Thermal	Mechanical	45
Gas turbine (industrial / aircraft)	Chemical	Mechanical	30 / 35
Automobile engine	Chemical	Mechanical	25
Fluorescent lamp	Electricity	Light	20
Silicon solar cell	Light	Electricity	15
Incandescent lamp	Electricity	Light	5

Practical power plant

Consider an electric power plant. Chemical energy of fuel is first converted to thermal energy in the boiler; thermal energy is then converted to mechanical energy in the turbine; finally, mechanical energy is converted to electricity in the generator. Power plant efficiency is, therefore:

$$\varepsilon_{\text{power plant}} = \varepsilon_{\text{boiler}}\varepsilon_{\text{turbine}}\varepsilon_{\text{generator}}$$

= (Thermal / Chemical) (Mechanical / Thermal) (Electric / Mechanical) = (Electric / Chemical)



Entropy dumped here or here

Figure 2.9: Water/steam flow through a power plant. At right, a cutaway model of a cooling tower.

Now, heat your home most efficiently

1) Using electricity from distant power plant:

$$\varepsilon_{coal} = \varepsilon_{extraction}\varepsilon_{processing}\varepsilon_{transport}\varepsilon_{powerplant}\varepsilon_{transmission}\varepsilon_{electric\ heater} =$$
$$= (0.66)\ (0.92)\ (0.98)\ (0.35)\ (0.90)\ (1.00) = 0.19\,(19\ \text{percent})$$

$$\varepsilon_{oil} = \varepsilon_{extraction}\varepsilon_{processing}\varepsilon_{transport}\varepsilon_{powerplant}\varepsilon_{transmission}\varepsilon_{electric\ heater} =$$
$$= (0.35)\ (0.88)\ (0.95)\ (0.35)\ (0.90)\ (1.00) = 0.09\,(9\ \text{percent})$$

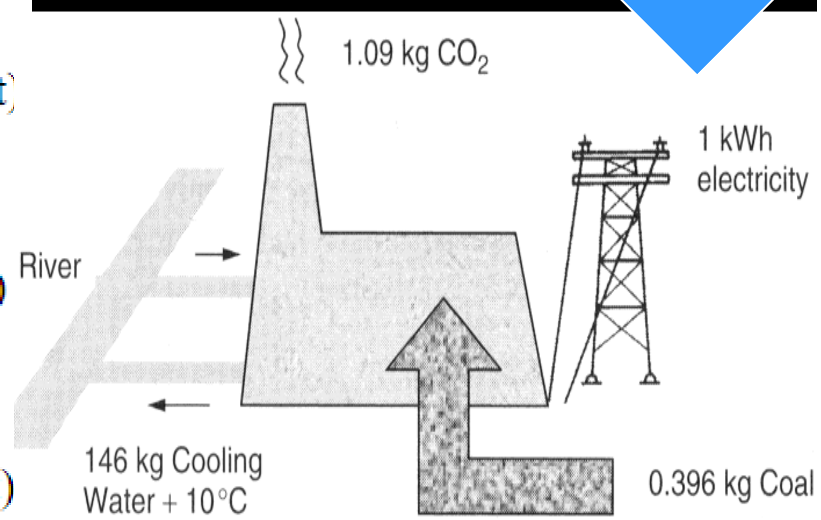
$$\varepsilon_{NG} = \varepsilon_{extraction}\varepsilon_{processing}\varepsilon_{transport}\varepsilon_{powerplant}\varepsilon_{transmission}\varepsilon_{electric\ heater} =$$
$$= (0.73)\ (0.97)\ (0.95)\ (0.35)\ (0.90)\ (1.00) = 0.21\,(21\ \text{percent})$$

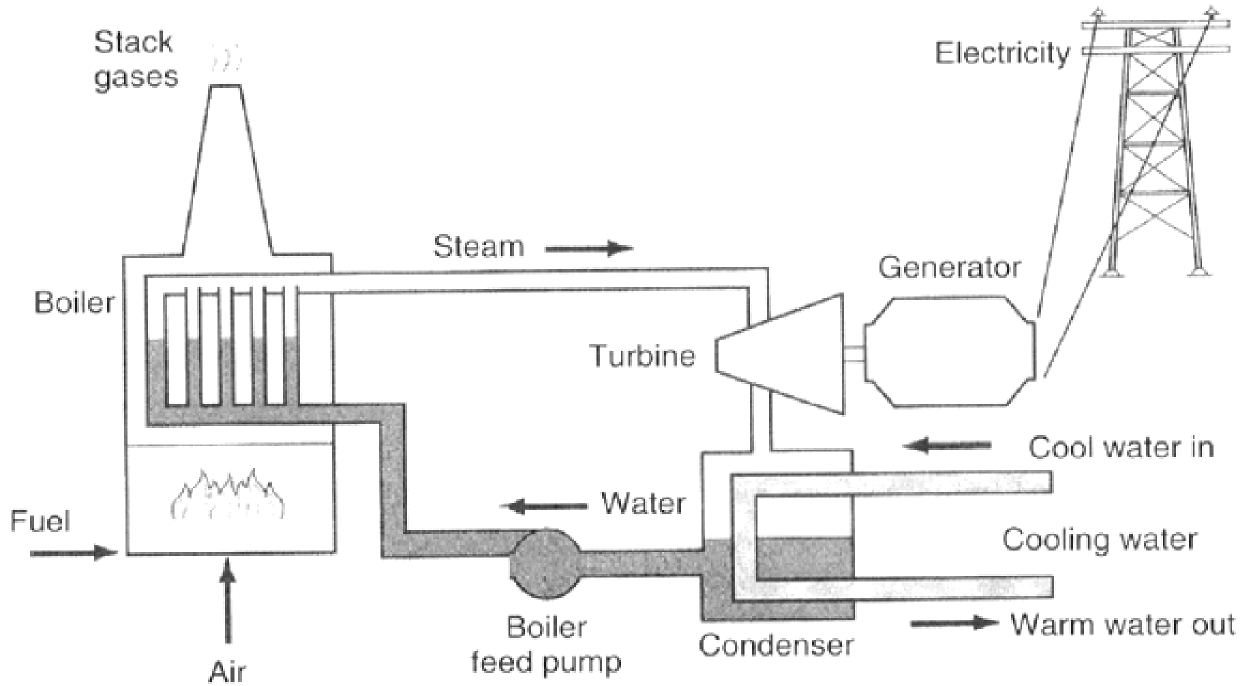
2) Using heat from home furnace:

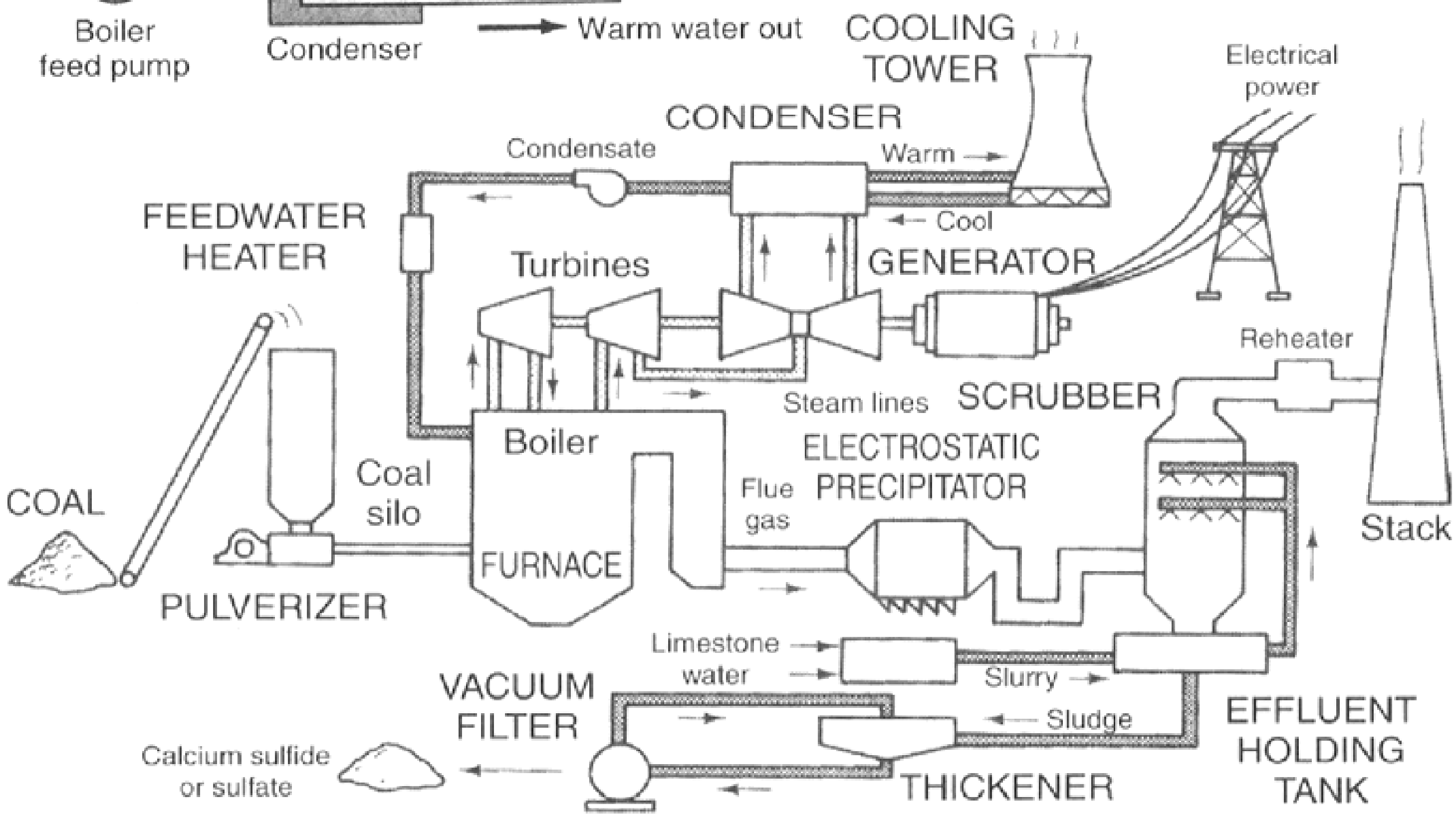
$$\varepsilon_{coal} = \varepsilon_{extraction}\varepsilon_{processing}\varepsilon_{transport}\varepsilon_{furnace} =$$
$$= (0.66)\ (0.92)\ (0.98)\ (0.55) = 0.33\,(33\ \text{percent})$$

$$\varepsilon_{oil} = \varepsilon_{extraction}\varepsilon_{processing}\varepsilon_{transport}\varepsilon_{furnace} =$$
$$= (0.35)\ (0.88)\ (0.95)\ (0.65) = 0.19\,(19\ \text{percent})$$

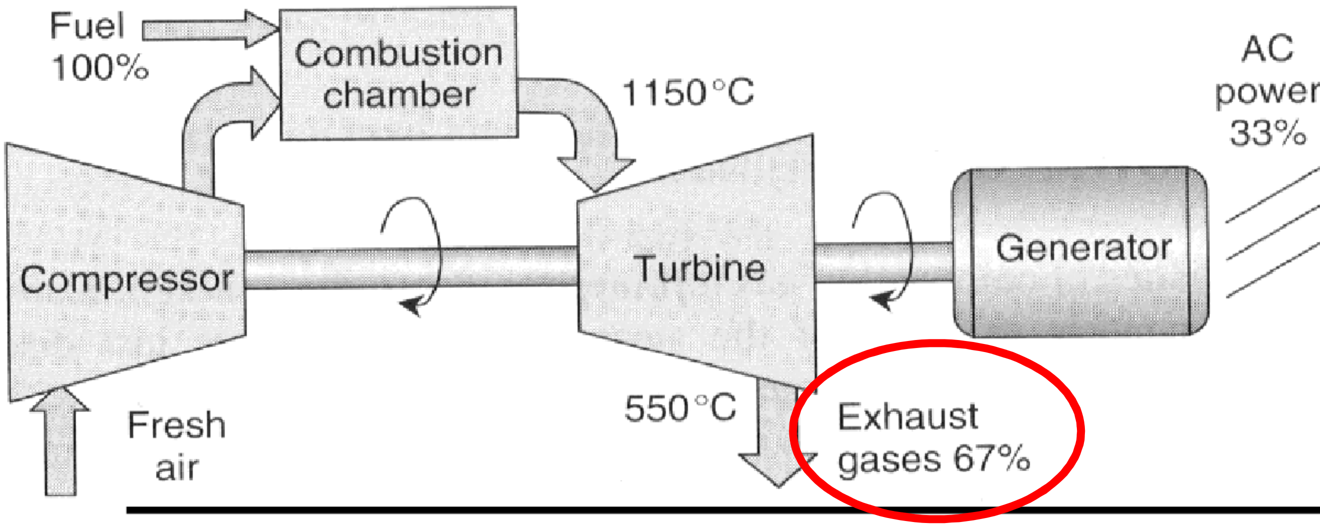
$$\varepsilon_{NG} = \varepsilon_{extraction}\varepsilon_{processing}\varepsilon_{transport}\varepsilon_{furnace} =$$
$$= (0.73)\ (0.97)\ (0.95)\ (0.92) = 0.62\,(62\ \text{percent})$$





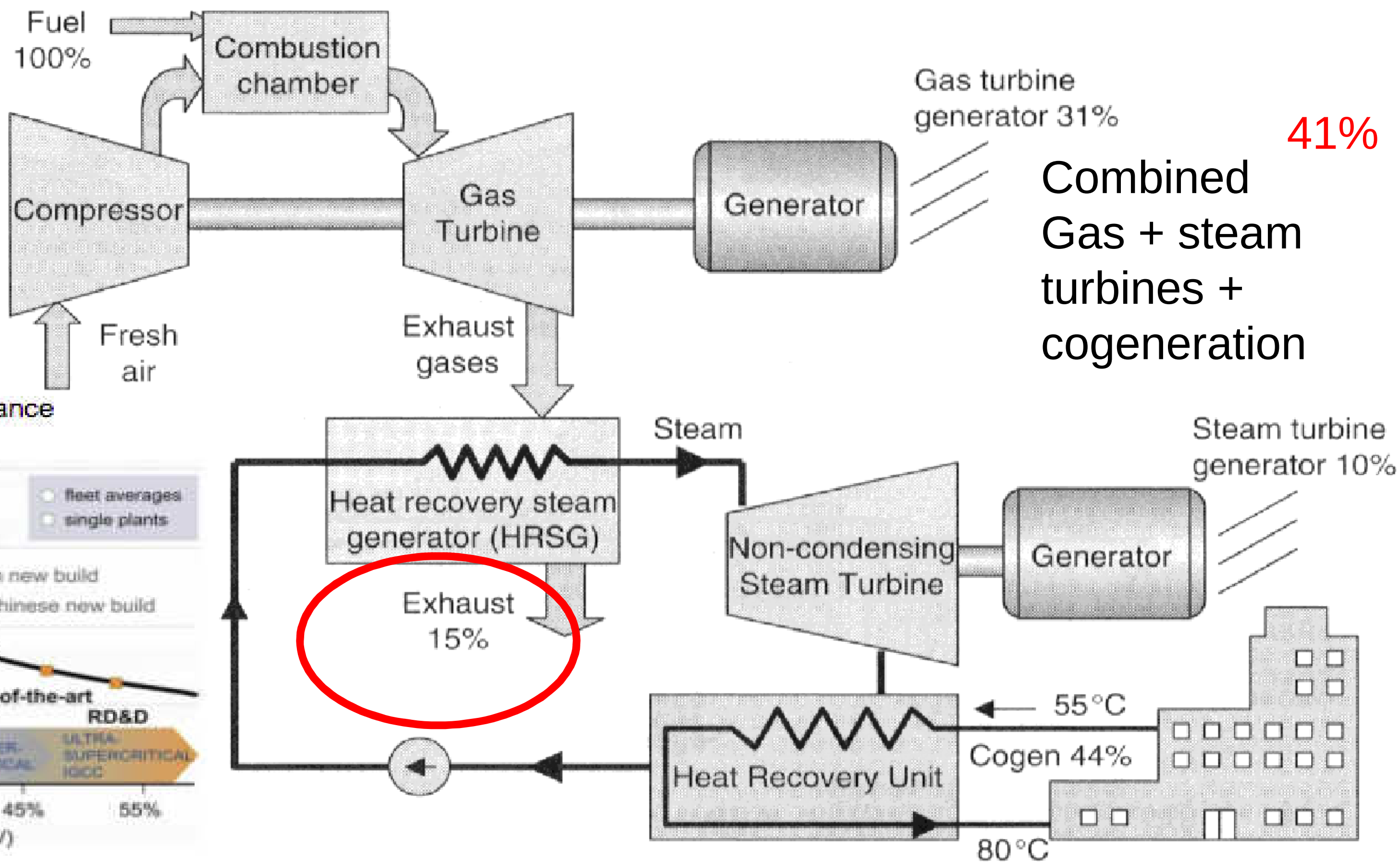


Clean up coal, only 5% hit on output power. Add CO_2 control, get 20% more hit.



33%

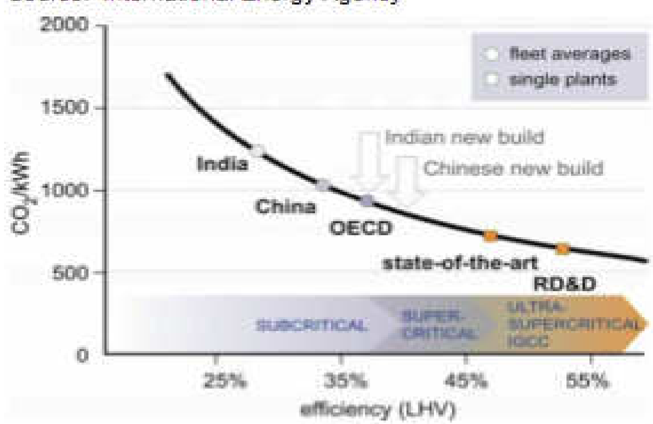
Gas turbine



41%

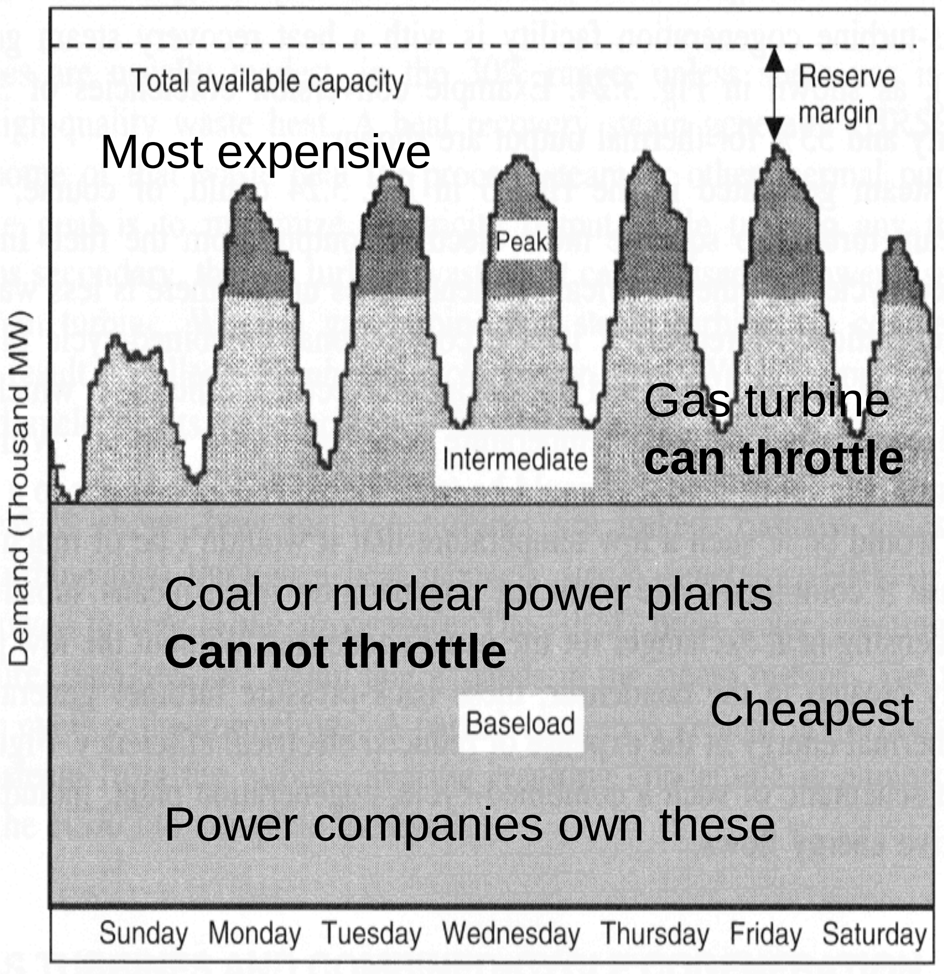
Combined Gas + steam turbines + cogeneration

Figure 1-3 Power plant performance
Source: International Energy Agency



Types of electrical generation

Agile = more costly



Power companies

- May buy power from others form intermediate load, or may own them
- More expensive fuel & more wear/tear so more maintenance
- Peak is usually bought from indep power producers at premium cost. Peak is in afternoon/evening so e.g. solar must shift a few hrs

Power companies

Build power plants not energy plants

- size plant by maximum baseload power out (~GW)
  - when run @ fraction of optimum power, are less efficient
- But, you pay for energy used ($/kW h)

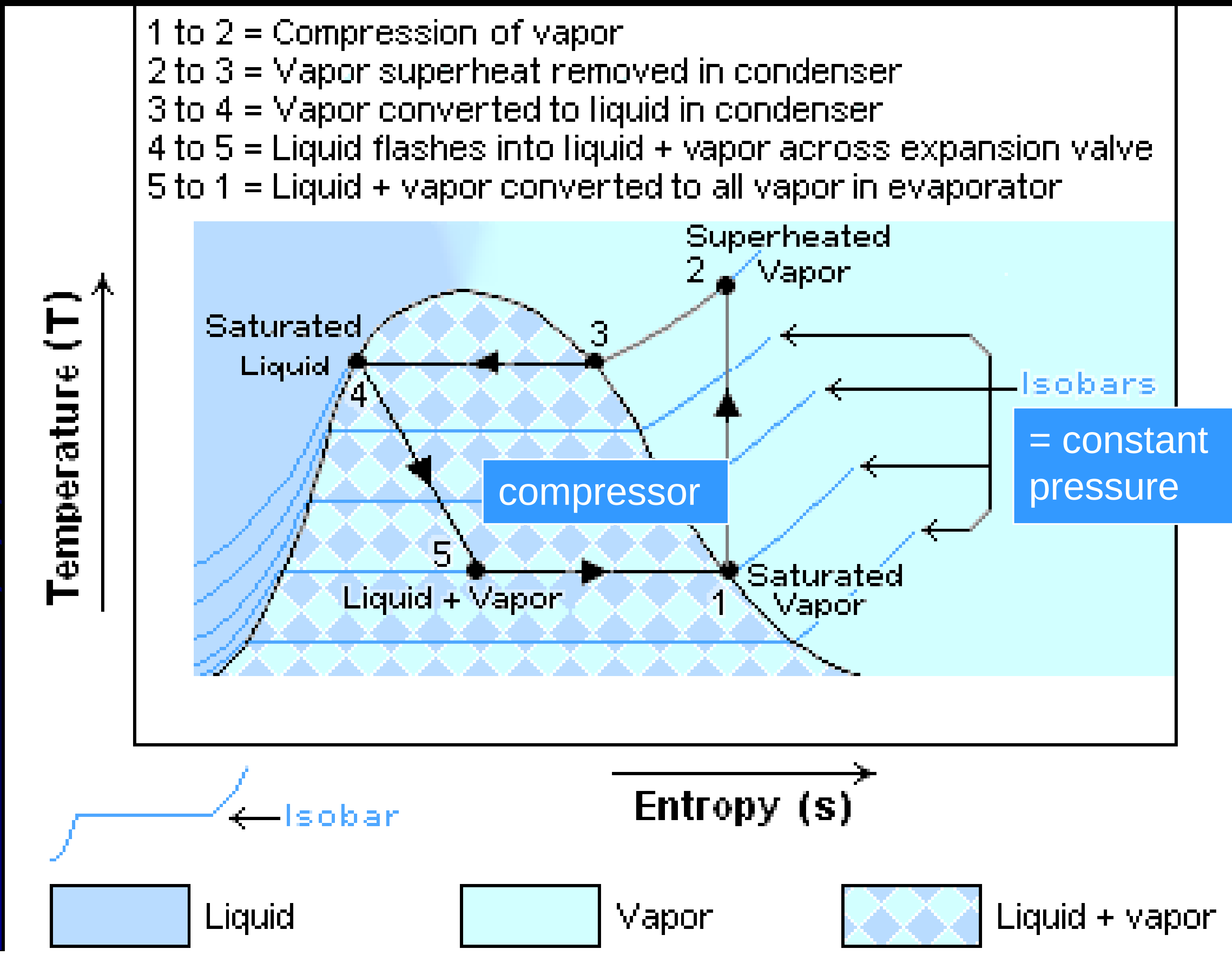
Non-renewable co$t set by energy stocks (~MW)

- Your bill = SUM of
  - sunk cost of plant (capital+interest paid over 40+ yrs)
  - Fuel costs (multi-year contracts)

Renewable co$t set by energy flow = power

- NO fuel cost, entirely sunk cost
- Technology changes quickly, so
  - more frequent upgrade $ capital, but less interest paid

Work -> Heat : Rankine backwards = refrigerator (or heat pump)

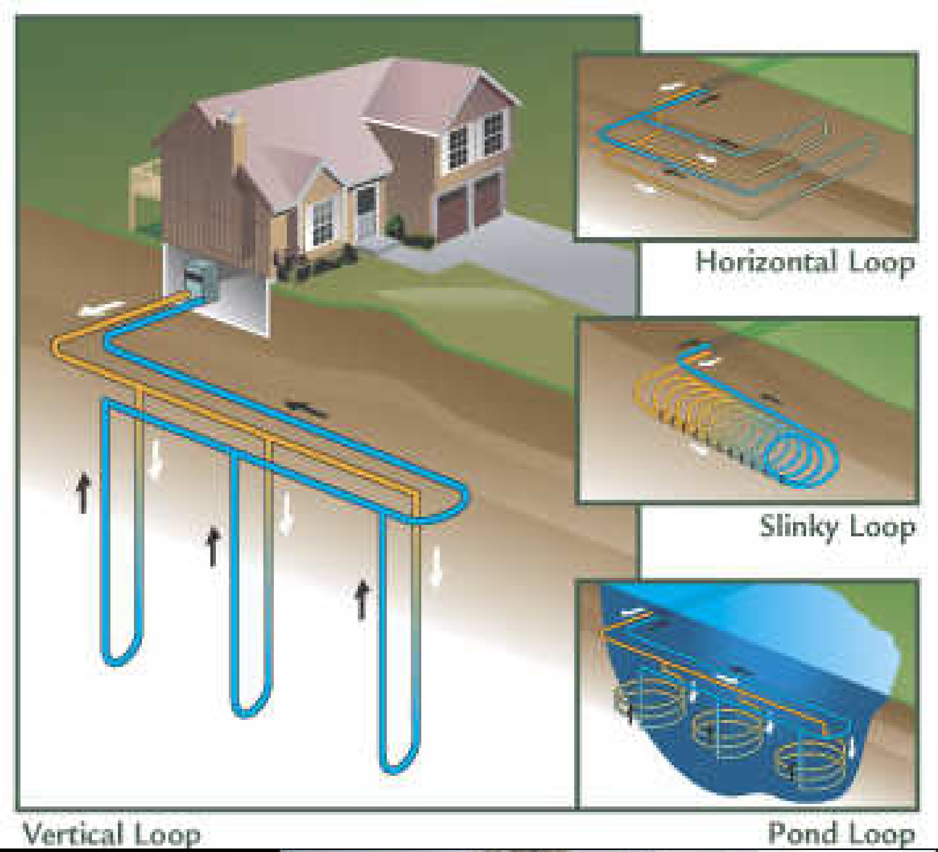


Heat pump = heat mover

- Low entropy -> High is very efficient
- Efficiency $$\eta = \frac{T_H}{T_H - T_L} > 1!$$
- When $T_H \sim T_L$ gain 2-3x over electric heater
  - So NG-fired powerplant+HP -> as efficient as home NG furnace
  - Heat pump when run backwards is AC
  - Efficiency drops quickly as air T_L drops to 0 °C in common units. Works best in moderate climate SC
- Ground source: in NC 1 ft into soil $T_L \sim 15$ °C = 288K

Ground loop & air loop heat pumps

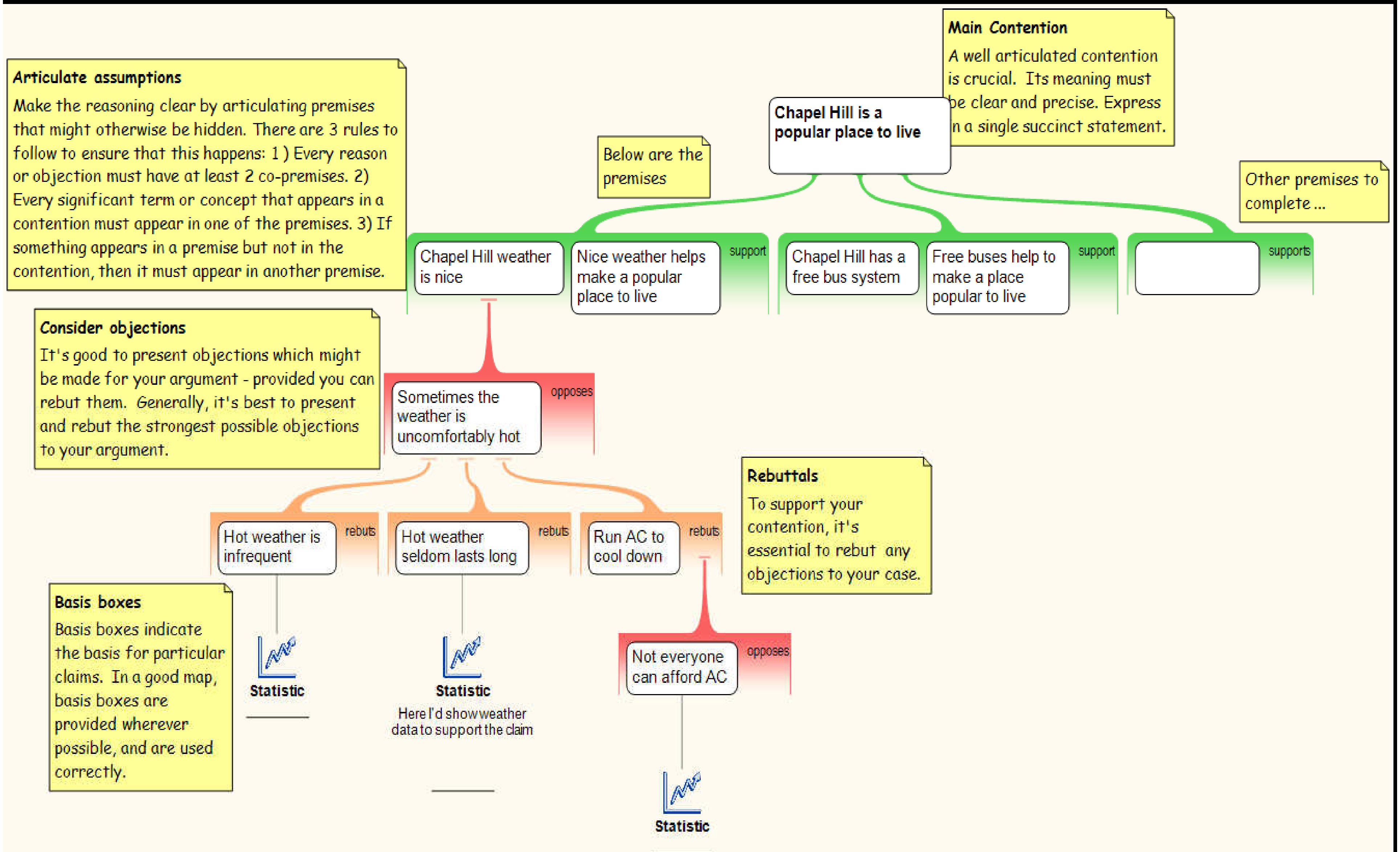
- Expensive excavation
- Very reliable & efficient
- Being replaced with super-efficient air loop
  - -10 to 24℃



Wed: Critical thinking by mind-mapping

- Software structures a logical argument
- Allows easy elaboration of “argument tree”
- Guides you to make all assumptions explicit
- Guides you to assess reliability/authority of all links
- Practice, practice, practice!

Analysis : trivial example



This is very useful Rationale® software,

Fossil fuels

1. Petroleum & Natural Gas

Origin

Discovery

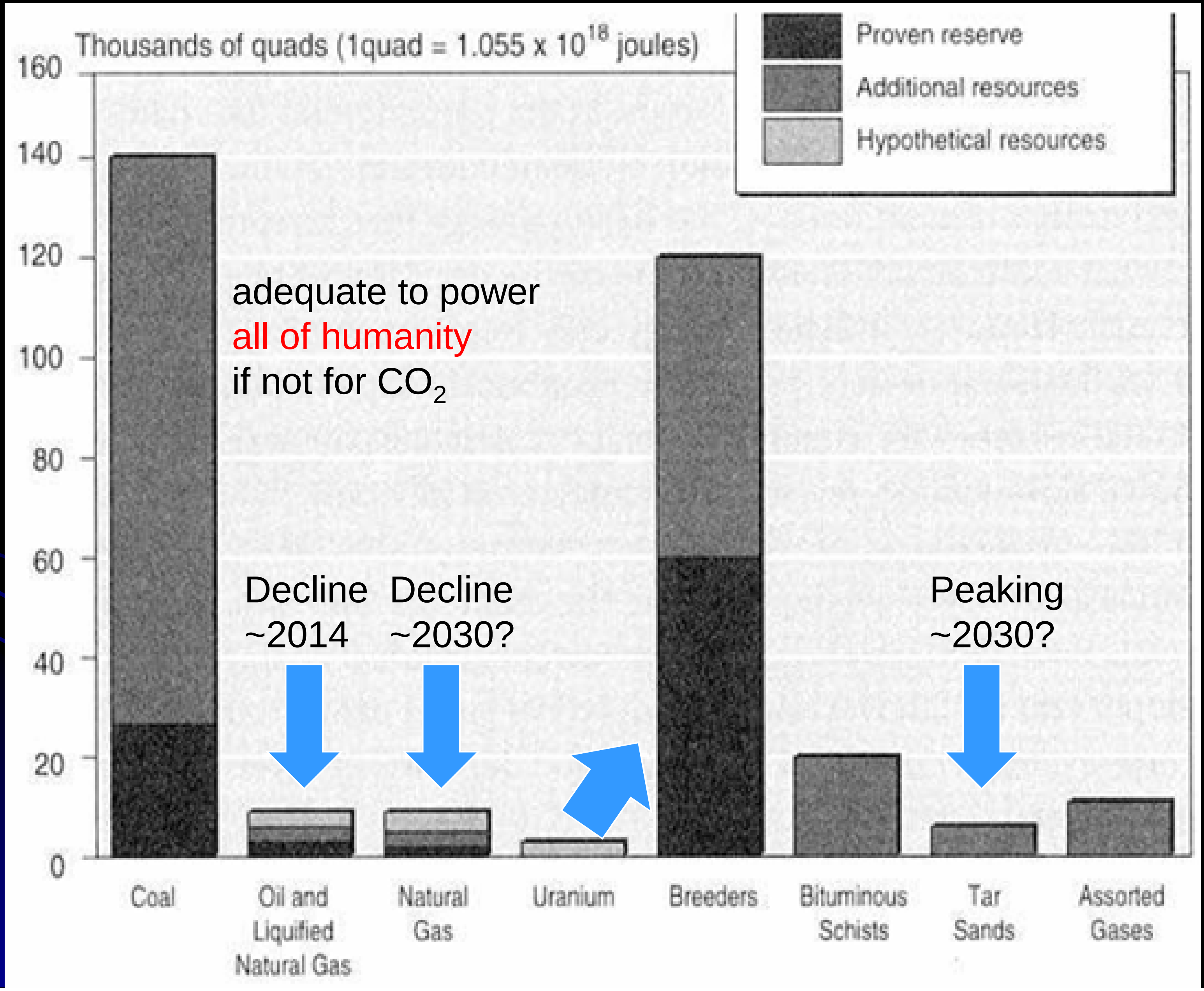
Extraction (depletion)

Predictive Model (Not my work!)

“It is only out of pride or gross ignorance, or cowardice, that we refuse to see in the present the lineaments of times to come.“

Marguerite Yourcenar

Plenty of Fossil Fuels!



Large, formerly balanced CO_2 flows

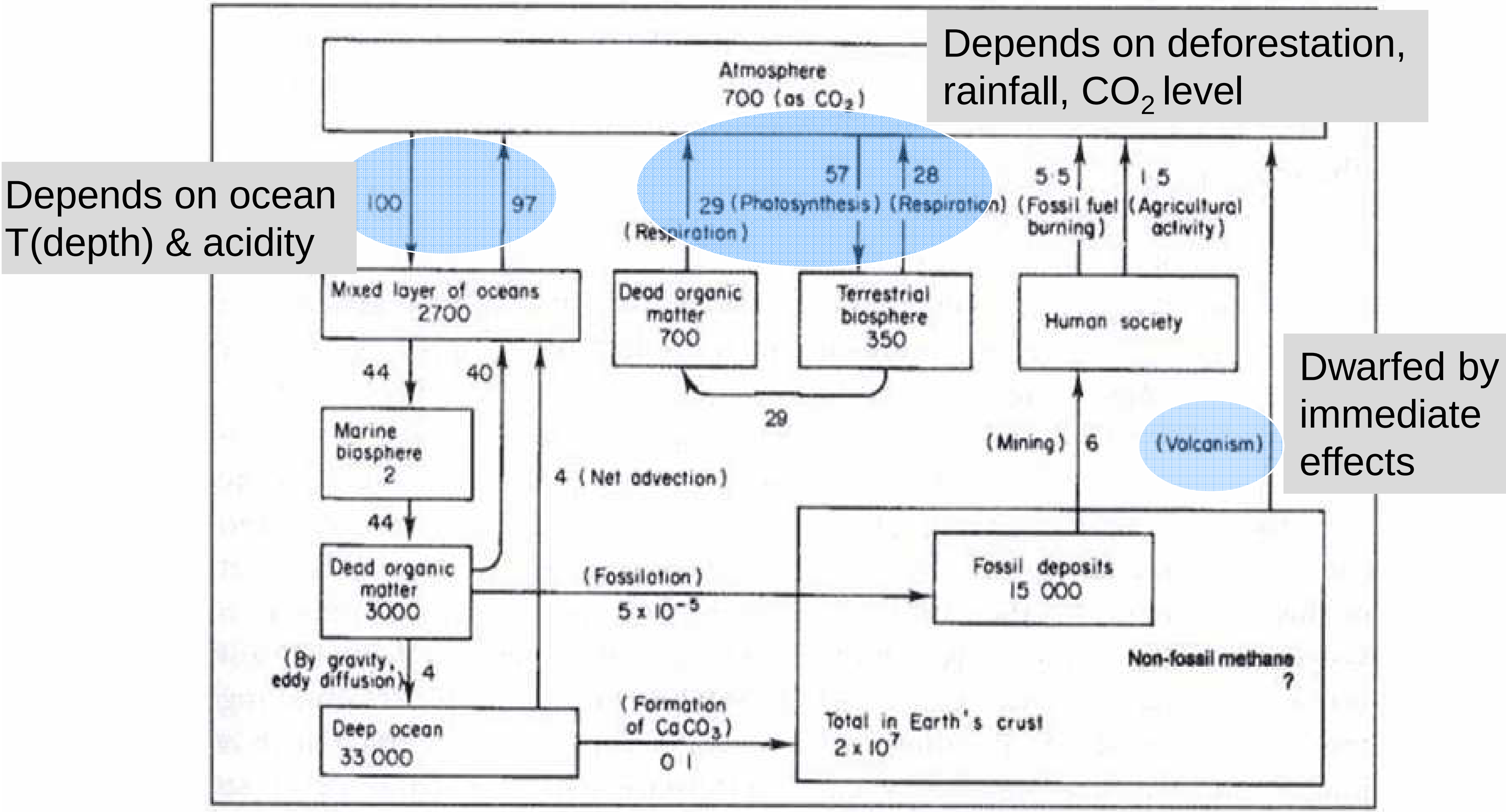
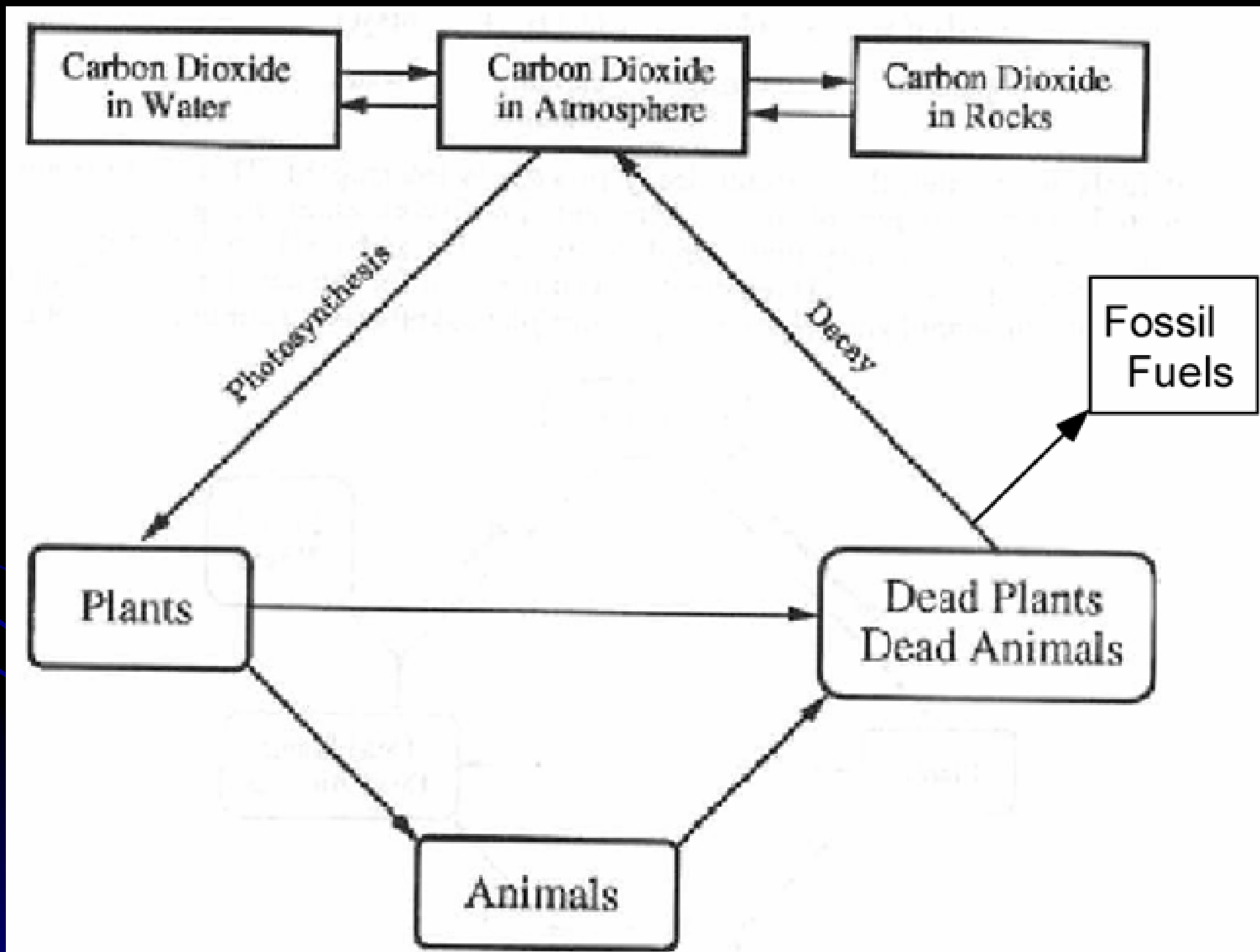


Figure 5.4: The carbon cycle quantitatively (units are 10^{12} kg of carbon stored and $10^{12}/yr$ transfered), showing the relatively small but critical human component in the context of the whole cycle.

Global Carbon Cycle



Fossil Fuels Origin

Almost completely biogenic (carbon cycle)

- Plants absorb CO_2 + water + sunlight to build organic C-H hydrocarbons (inorganic here is C w/o H)
  - inefficient : photons too energetic for direct plant use → chemical energy (sugar & other metabolic molecules)
  - Storage is chemical reduction
    - Sunlight + $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$
    - Energy is held in C-C & C-O & C-H electron bonds
- Cycle completes by aerobic decay (oxidation)
    - $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ + energy of old sunlight
- If oxidation interrupted, get fossil fuel source rock
  - We choose when to complete oxidation & so release bound energy as electrons redistribute

!!! geological processes concentrate fuels

For Abundant Growth, Need

- Abundant light (photosynthesis)
- Warmth (high bioproductivity)
- Moisture (good nutrient flow)

Optimal environments: sub/tropical swamps, river deltas, lakes, reef lagoons, shallow seas

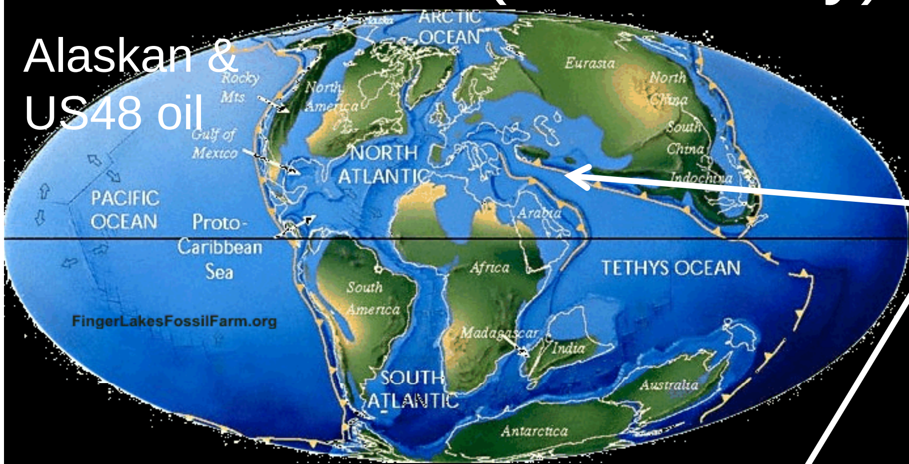
Each produces unique type of fossil fuel 10s Myr later:
Marine algae: oil Land biomass: coal Both: NG
+heat

$$$ implications: distribution/concentration sets energy needed to extract fuel, & contaminants that complicate refining

Such regions in past formed all oil/NG!

Cretaceous (120-94 My)

Alaskan & US48 oil

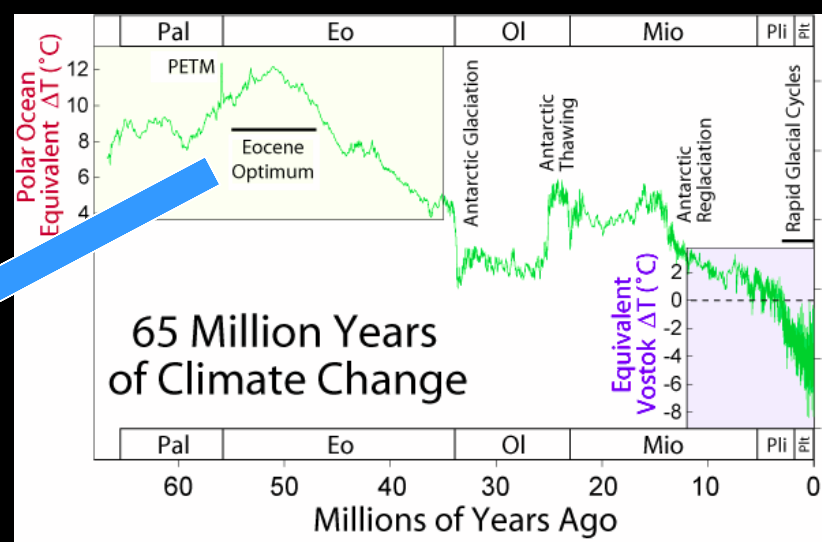


Flooded continental shelves, many shallow seas

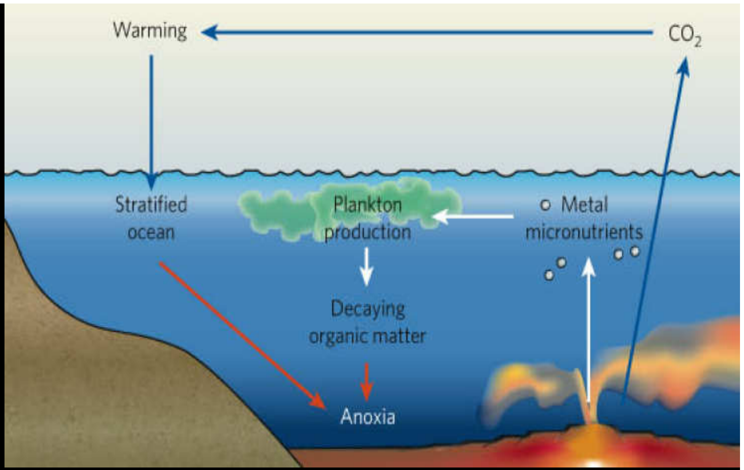
Note: Middle East & "Stans" were tropical, shallow, prolific in both intervals

Today SE Asia, N. of Australia making oil ready 10s Myr from now

Paleocene (55-45 My)



No oxidation → need oceanic anoxic events

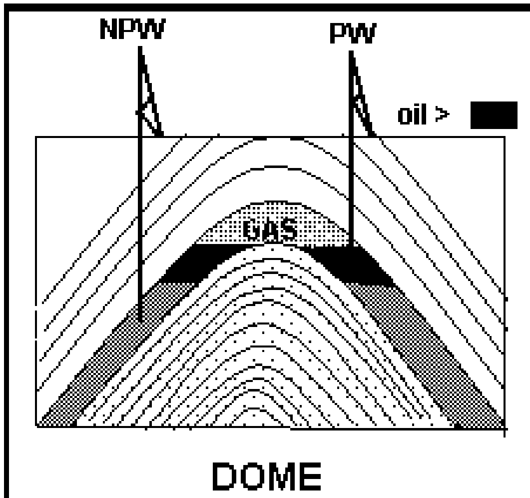


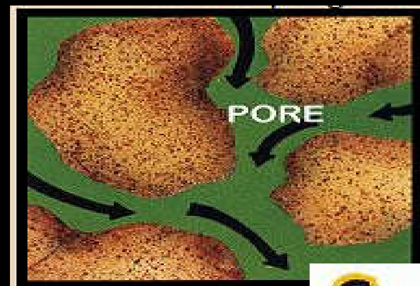
- "super-greenhouse" eras
  - Under-sea volcanism 30-50x today boosted CO_2 atmosphere levels 60% higher than today (650 ppm)
    - ~twice our pre-industrial
    - At first enhanced bio-productivity, then …
    - … over few thousand yrs raised sea T, attenuated major ocean circulation currents
      - Less vertical circulation: oceans were O starved deeper than ~200 m, few bottom dwellers to scavenge
    - Volcanic hydrogen sulfide further poisoned oceans
  - Organic debris settled without oxidation
    - Made widespread black shale deposits (oil source rock)

In this picture, petroleum is rare

- Shale (kerogen) buried, compressed, cooked in crust. Higher T + water broke long C chains to smaller ones (>2 km burial)
  - Kerogen in air = oil shale, buried = bitumen
- Regions that stay cool long enough form petroleum (80/90% oil/NG worldwide @ T = 60-120°C: golden zone)
- If faulted, can flow & pool. If cap rock, NG+ petroleum+water stratifies, pressurizing oil
- If T ever too high (>5 km), petroleum soon cracks to NG, generally lost into atmosphere

Concentrating Oil in Rock Pores





- Oil/NG/water zones separate (stratify) by densities:
  - NG cap atop oil concentrate atop water
  - Oil pressurized by NG & slightly by water
  - If cap rock porous or surface erodes, NG escapes and oil stranded (= too expensive to pump out)
- Studied w/ 3D seismology :

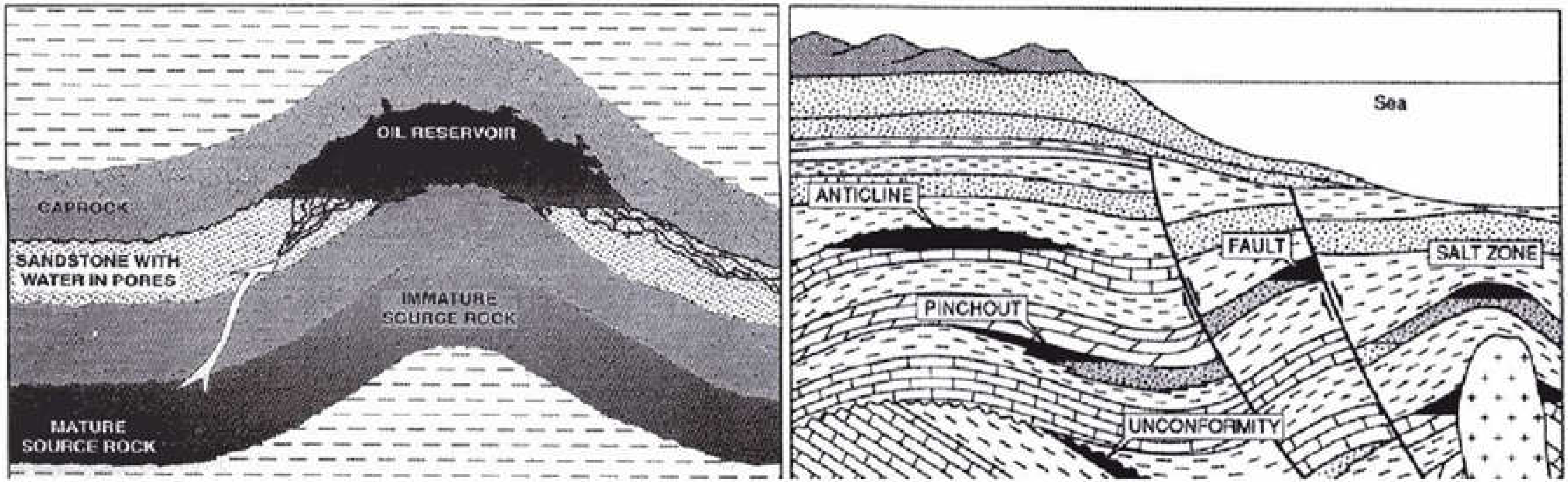
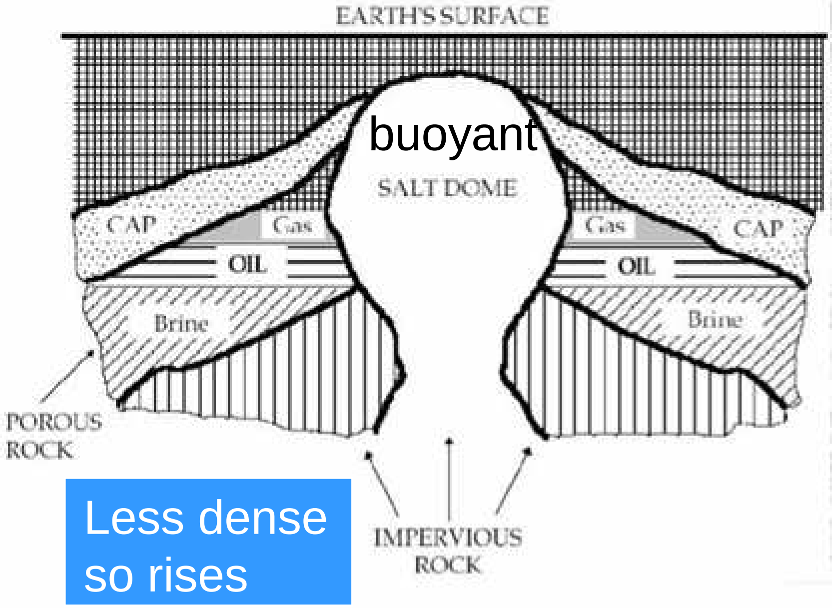


Figure 7.5: (left) Geology of an oil trap. (right) Gentle folding to trap oil.



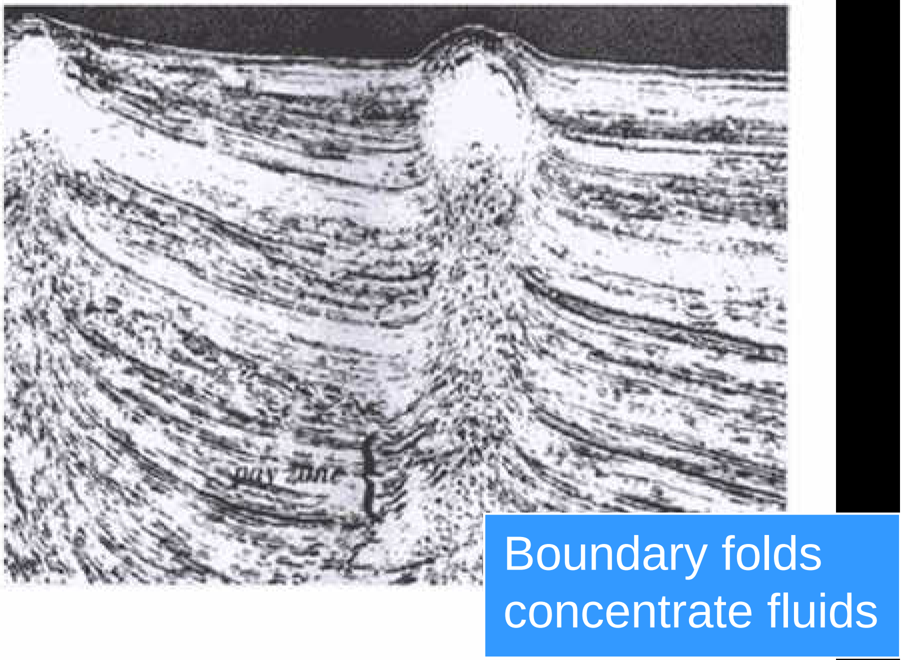
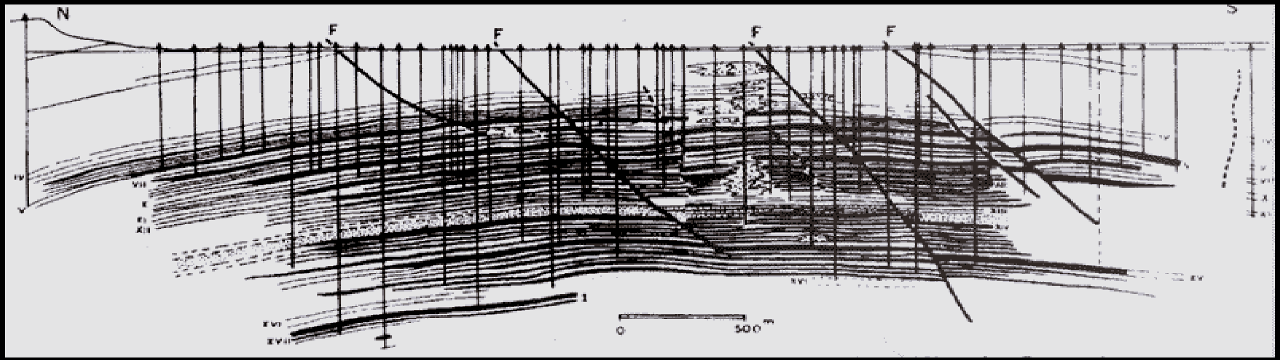


Figure 7.9: (left) Representative geologic structure of an oil trap: a salt dome. (right) A seismic image, showing several salt domes as well as possible oil traps near their base.

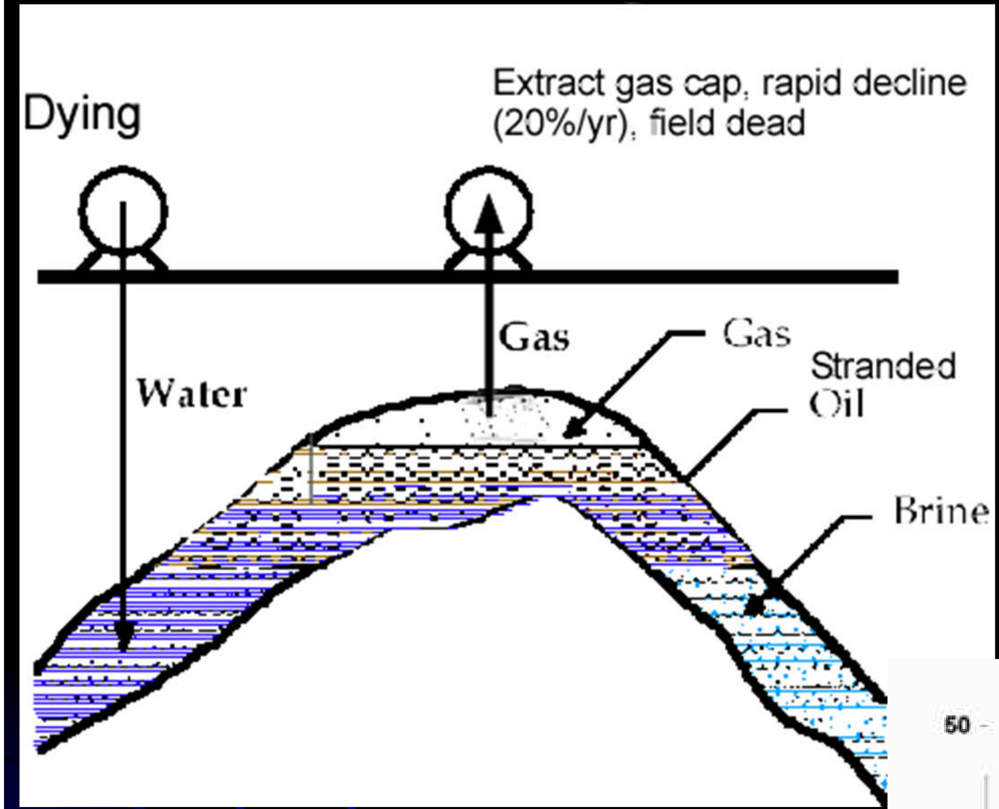
Oil & NG Extraction

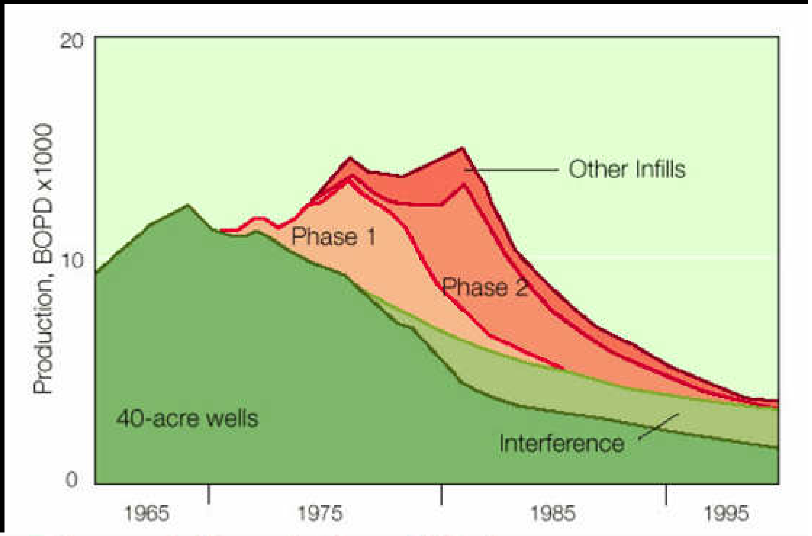
- "Wildcat" test wells (90% duds, lose $ but <u>write-off</u>)
  - Drill bit, "mud", casing, directional drilling, block-back control, cap wells, "fracking"
  - marginal wells (bottom/sides) define extent pay zone

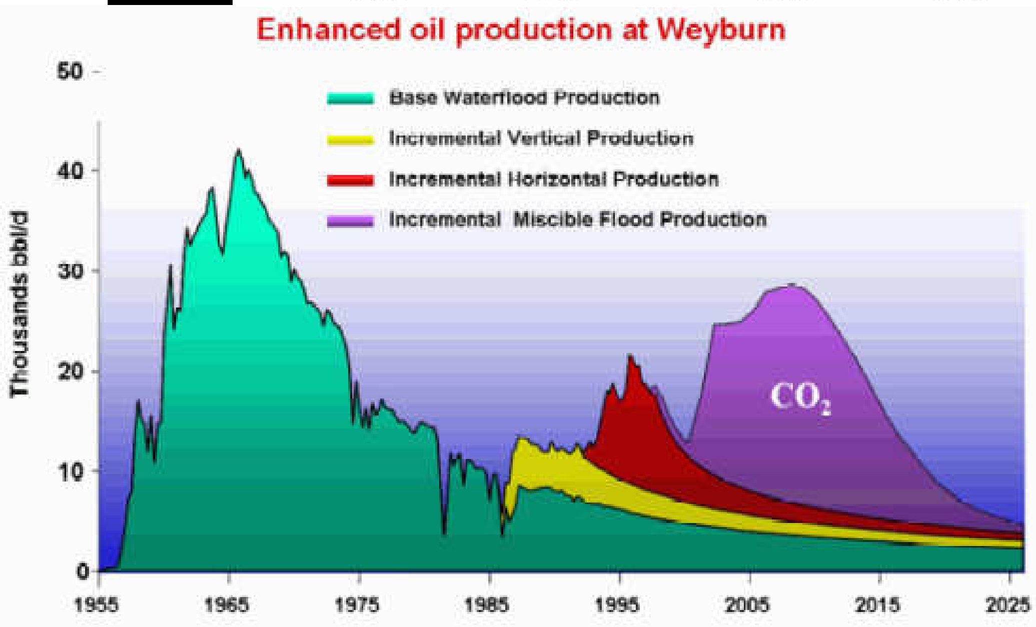


  - Primary extraction gets <= 30% of oil in place (OIP)
- Repressurize field by injecting water/gas. Sweeps oil to wells (secondary extraction) increases to ~50% OIP
- Tertiary recovery: inject detergents/steam/CO_2
- Finally remove NG cap, stranding 30-40% OIP

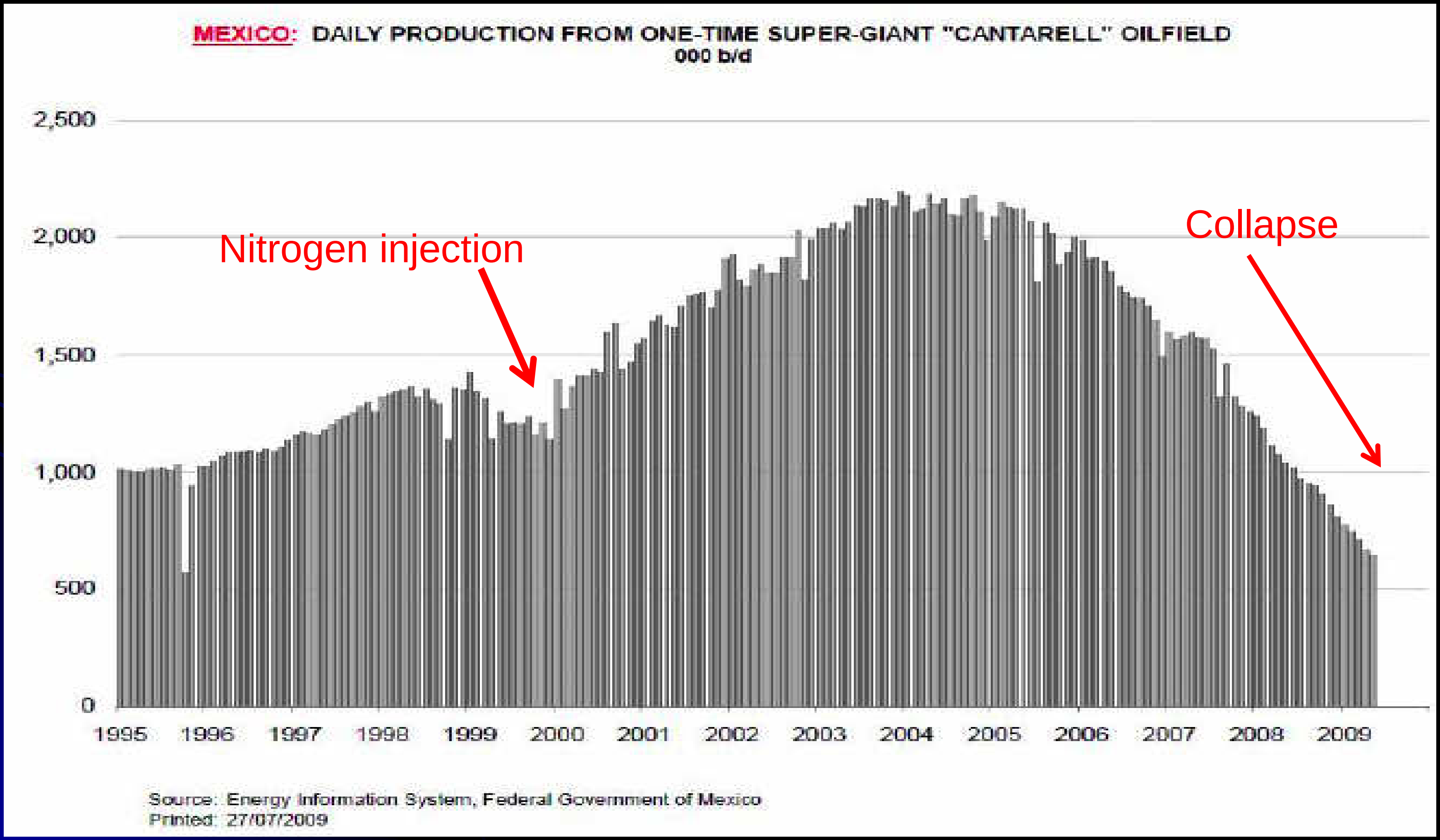
Draining Oil/NG Field



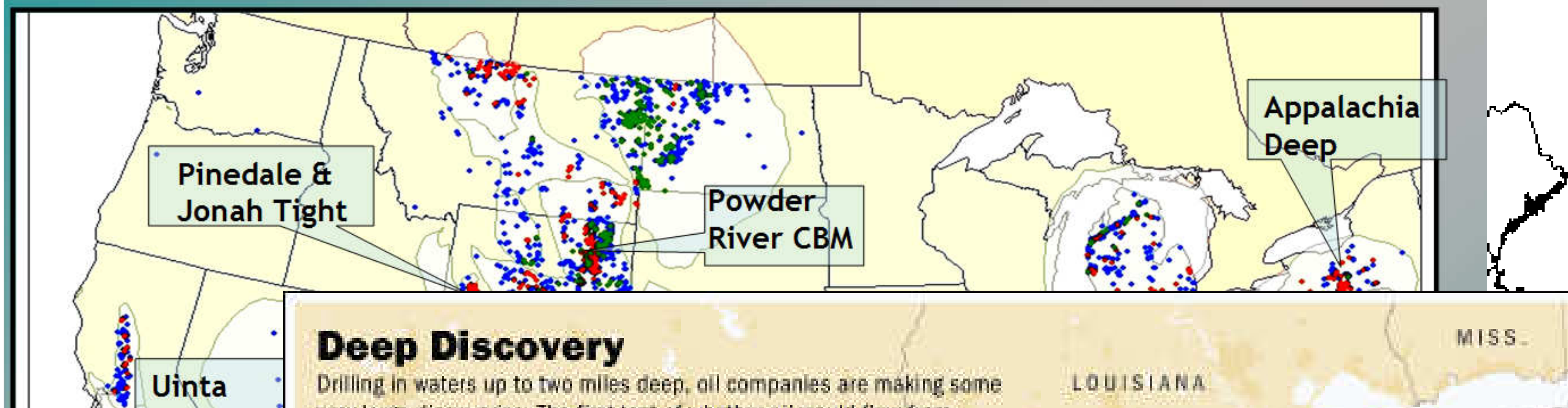


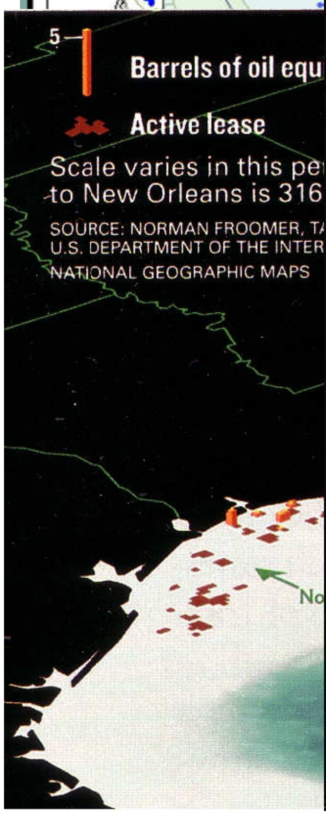


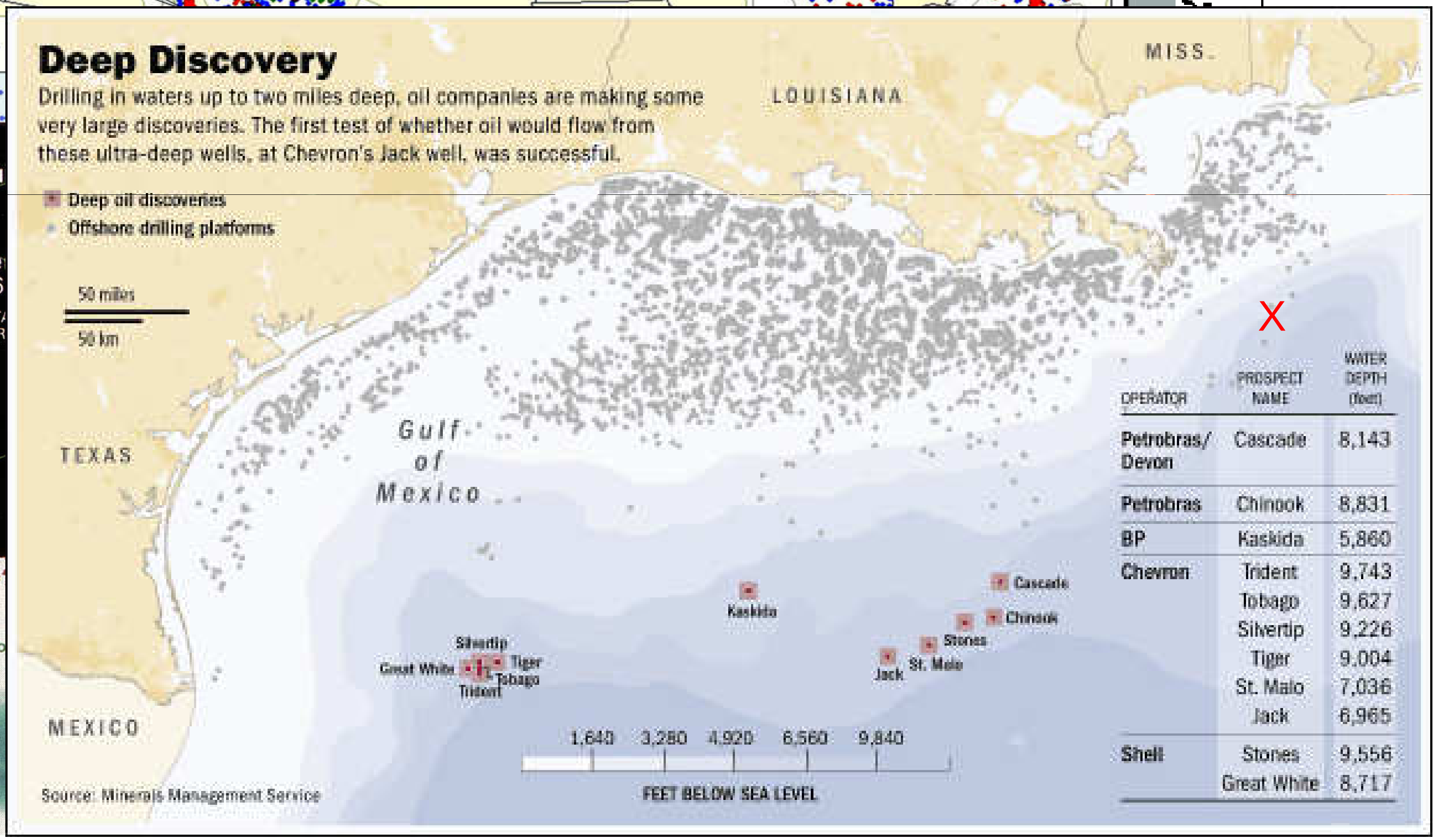
Another example



Most Active US Drilling Areas





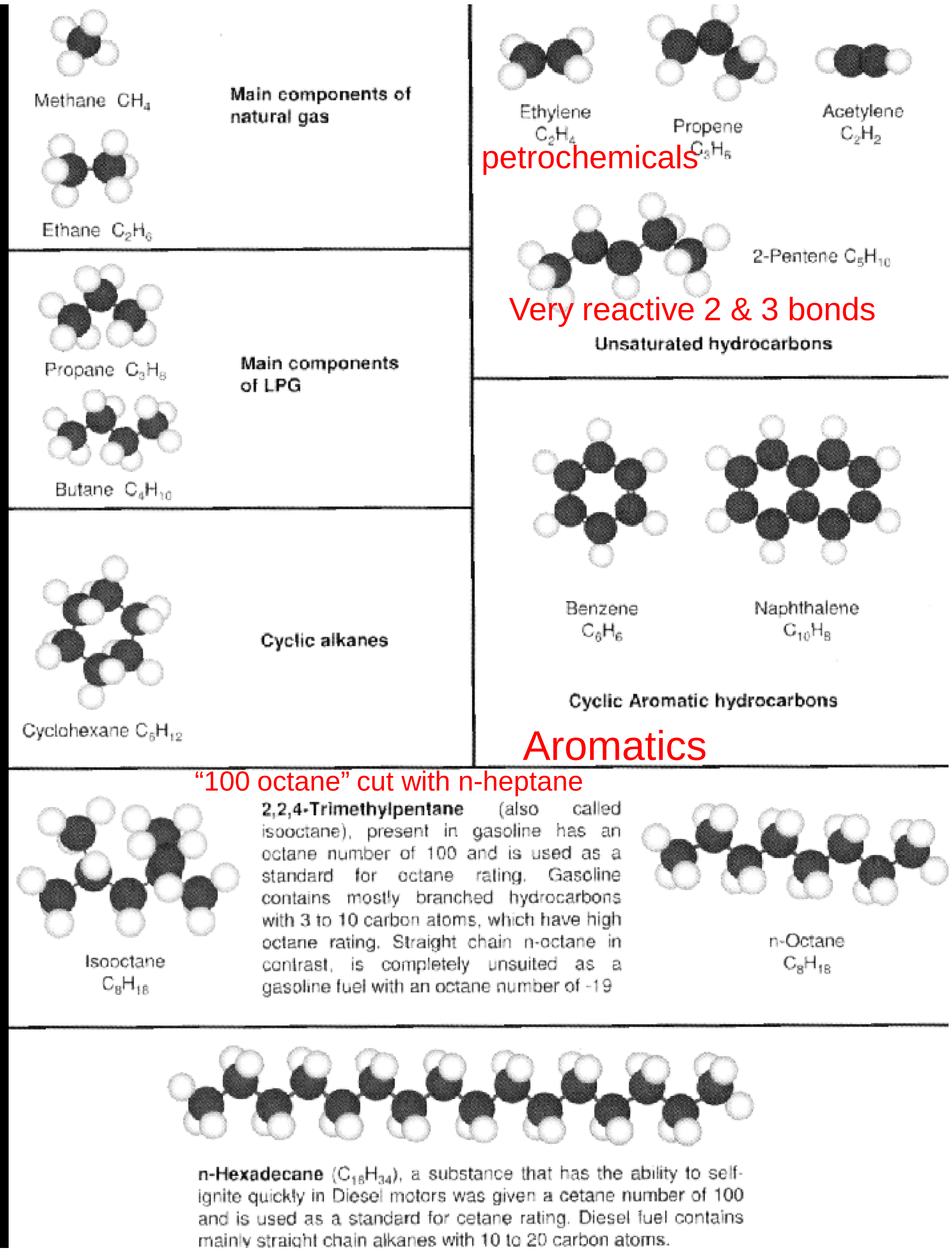


Petroleum & NG structure

Enough C atoms make molecule heavy enough at room T to form liquid (convenient)

Gas requires heavy Container (costly)

Energy is released as H-H & C-C bonds snap & electron clouds redistribute



Oil Refining

Flare lightest & NG (Iraq, done if no NG pipeline)

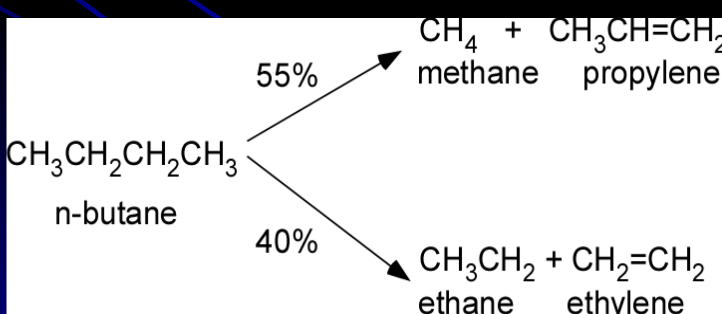
Vaporize crude oil @ 700 ℉

Molecules of different mass rise to different levels, repeat to increase concentration.

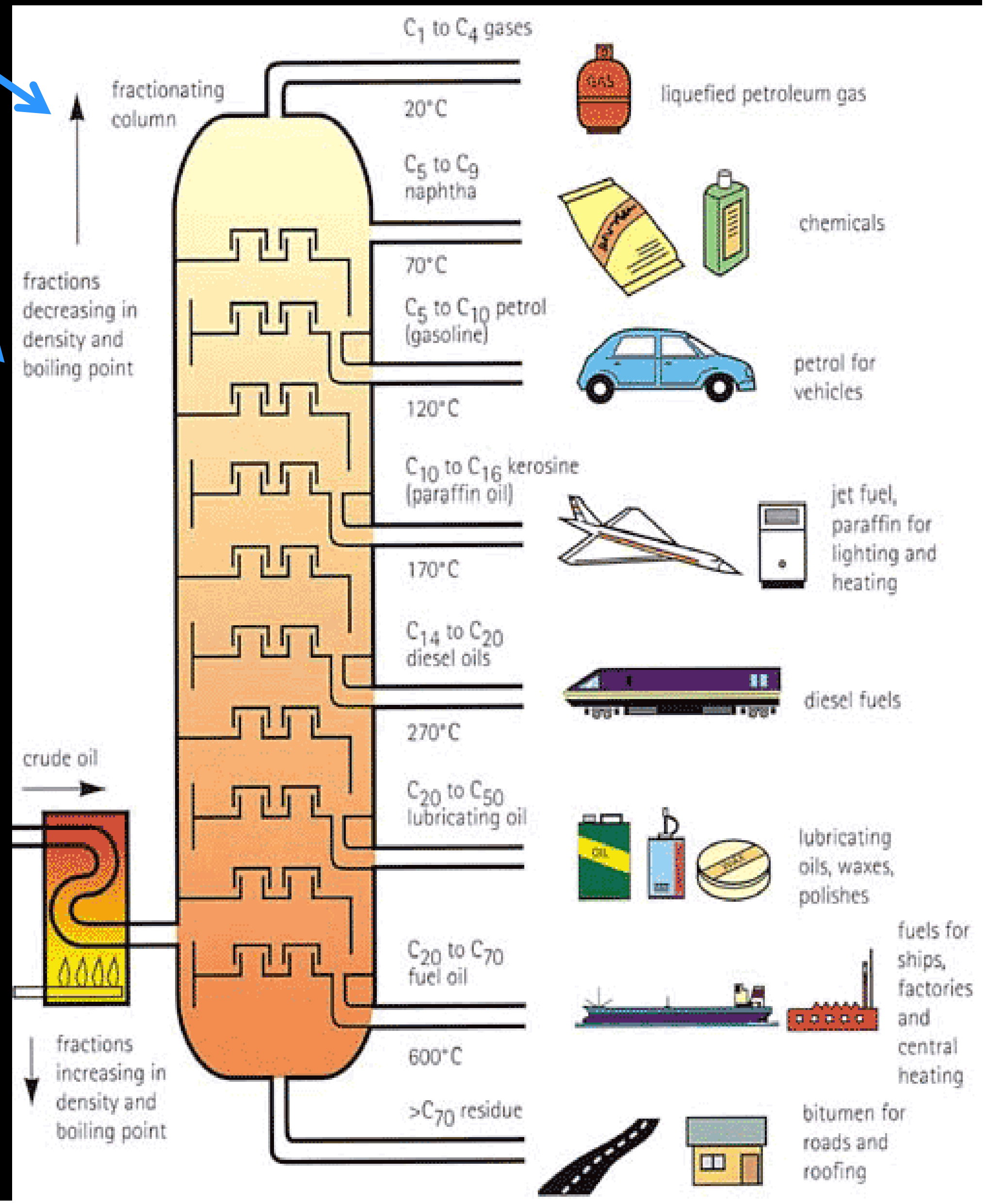
Coking removes C to increase H/C

Reforming improves octane #

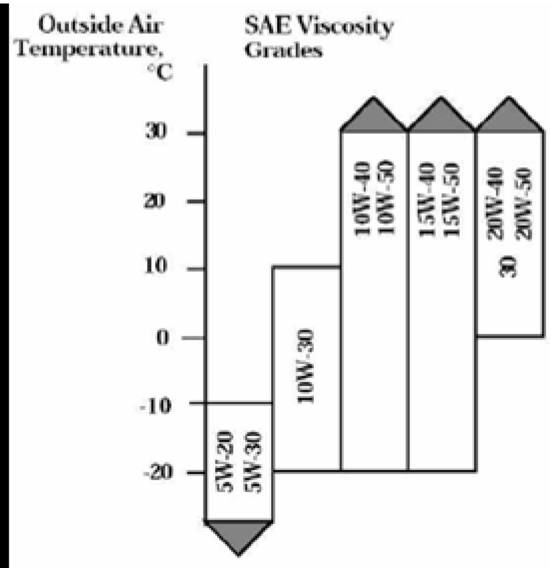
Crack & catalyze long chains to lighter



Goal: increase lighter, more widely useful & cleaner burning fraction



Using Petroleum



7.1: Principal energy-related uses of the products of oil refining

Product	Main use
Gases	Industrial & residential fuel
Gasoline	Fuel in spark-ignition engines
Diesel fuel	Fuel in compression-ignition engines
Jet fuel (Kerosene)	Fuel for jet engines & gas turbines
Fuel oils	Industrial or residential fuel

Number	Name	Color	Calorific value (BTU/gallon)
1	Kerosene	Light	137,000
2	Distillate	Amber	141,000
4	Very light residual	Black	146,000
5	Light residual	Black	148,000
6	"Residual (Bunker C)"	Black	150,000

ONE BARREL crude oil:

- enough gasoline to drive a medium-sized SUV (17 miles-per-gallon) 200 miles
- enough distillate fuel to drive a large truck (5 miles-per-gallon) nearly 50 miles
- enough liquified propane gas to fill 12 small cylinders
- nearly 70 kWe-h at a power plant generated by residual fuel oil
- asphalt to make one gallon of tar for patching roofs or streets
- about 4 pounds of charcoal briquets
- wax for 170 small birthday candles, or 27 wax crayons
- lubricants to make 1 quart of motor oil
- enough petrochemical left to make: 39 polyester shirts, 750 pocket combs, 540 toothbrushes, 65 plastic dustpans, 23 hula hoops, 65 plastic drinking glasses, 195 one-cup measuring cups, 11 telephone housings, 135 four-inch "rubber" balls
- one quart of paint thinner

2 squeezes on oil supply

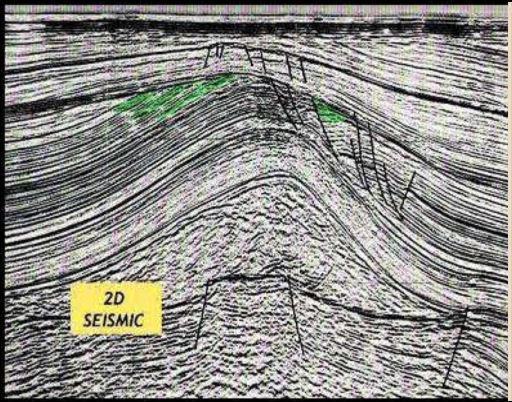
Global per capita power declining (flat energy supply consumed by growing pop.)

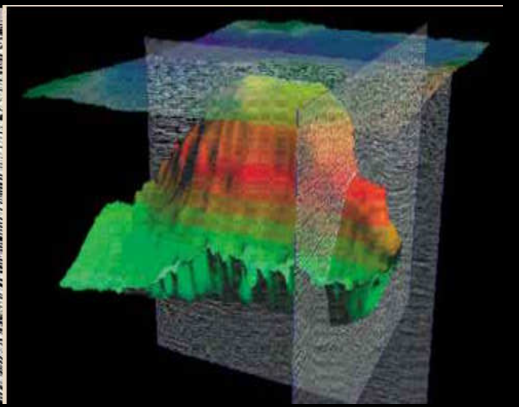
ERoEI is declining because we've drained most accessible concentrated oil reservoirs

- Larger effort expended extracting fuels
- More waste pollution preparing fuels
- Power infrastructure was optimized for fossil fuels, expensive in $, energy, & time to replace
  - Wasteful to junk so tend to refurbish
  - Entrenched business hence political interests often restrict scope of refurbishments

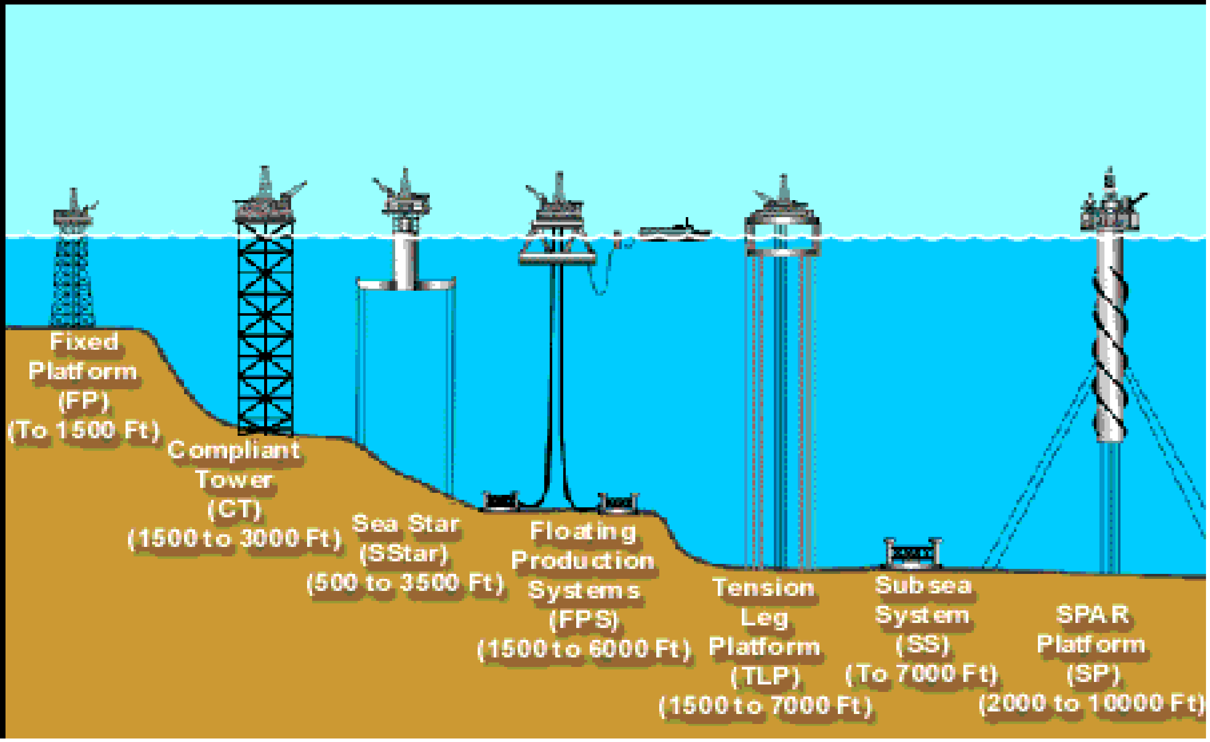
What Limits oil "Flow"?

- Discovery (seismic, 2D





- Off-shore drill rigs, complex so expensive so limited #

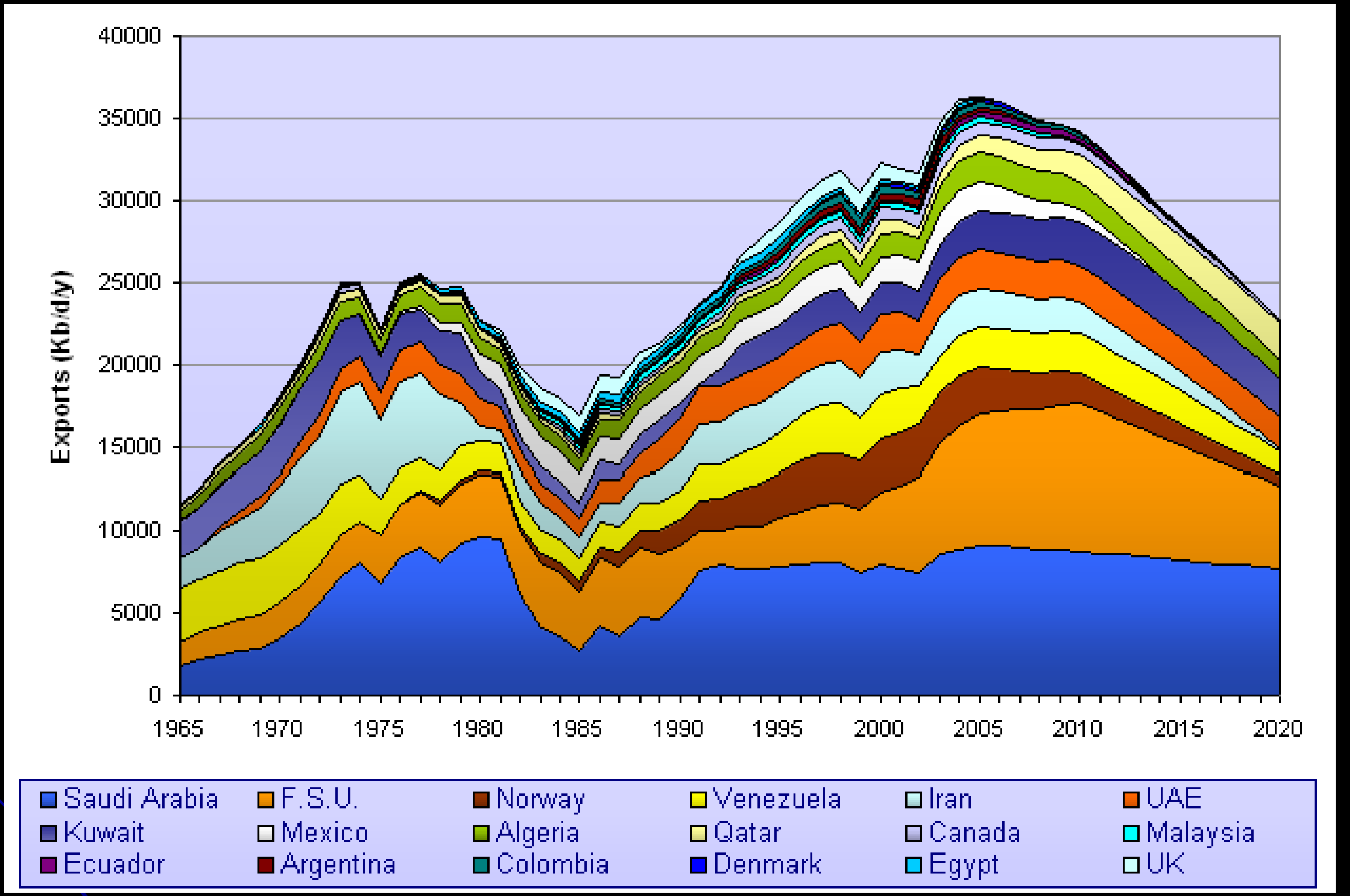


- Investment bubblers & Cartels
- Extreme weather damage

- No new refinerys (NIMBY)

- Inefficient use

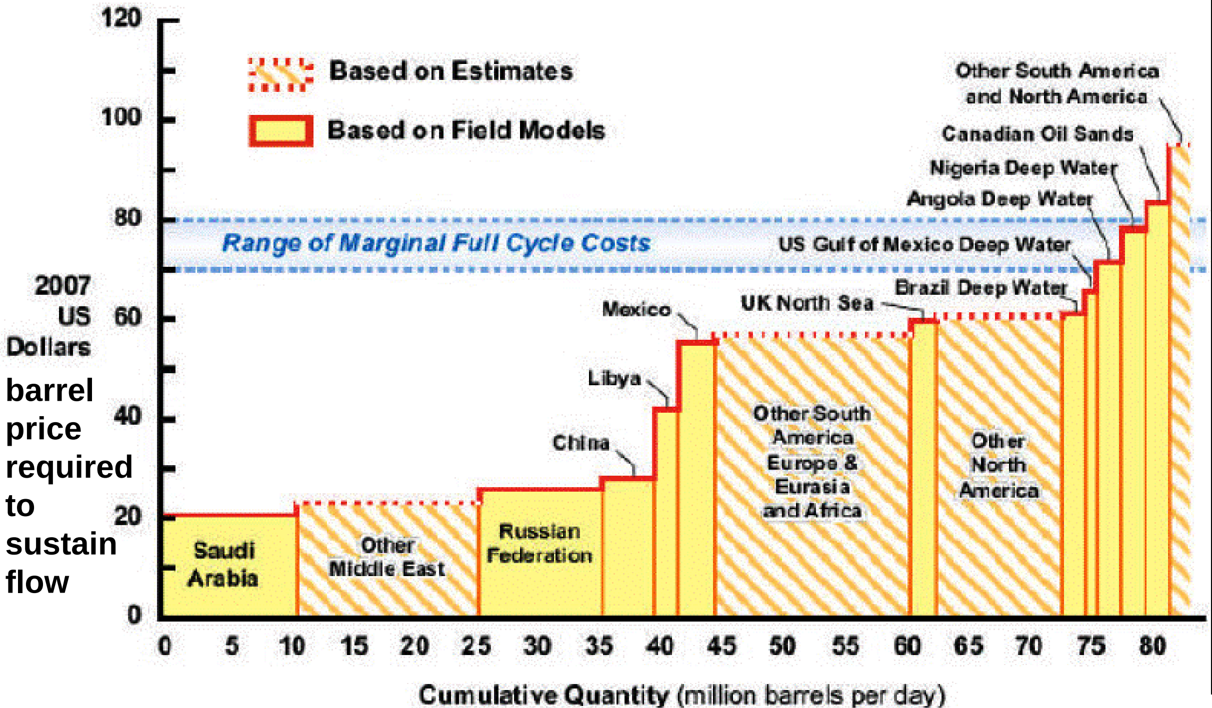
- Export restrictions to maintain domestic supply to consume “petrodollar” wealth

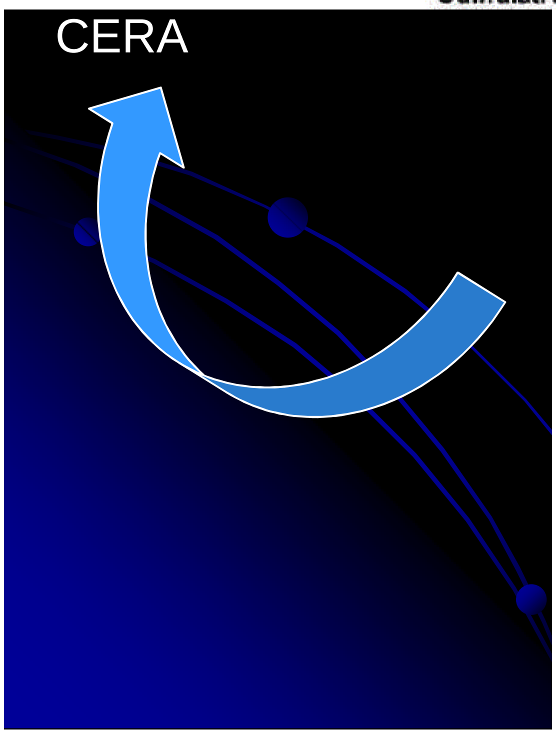


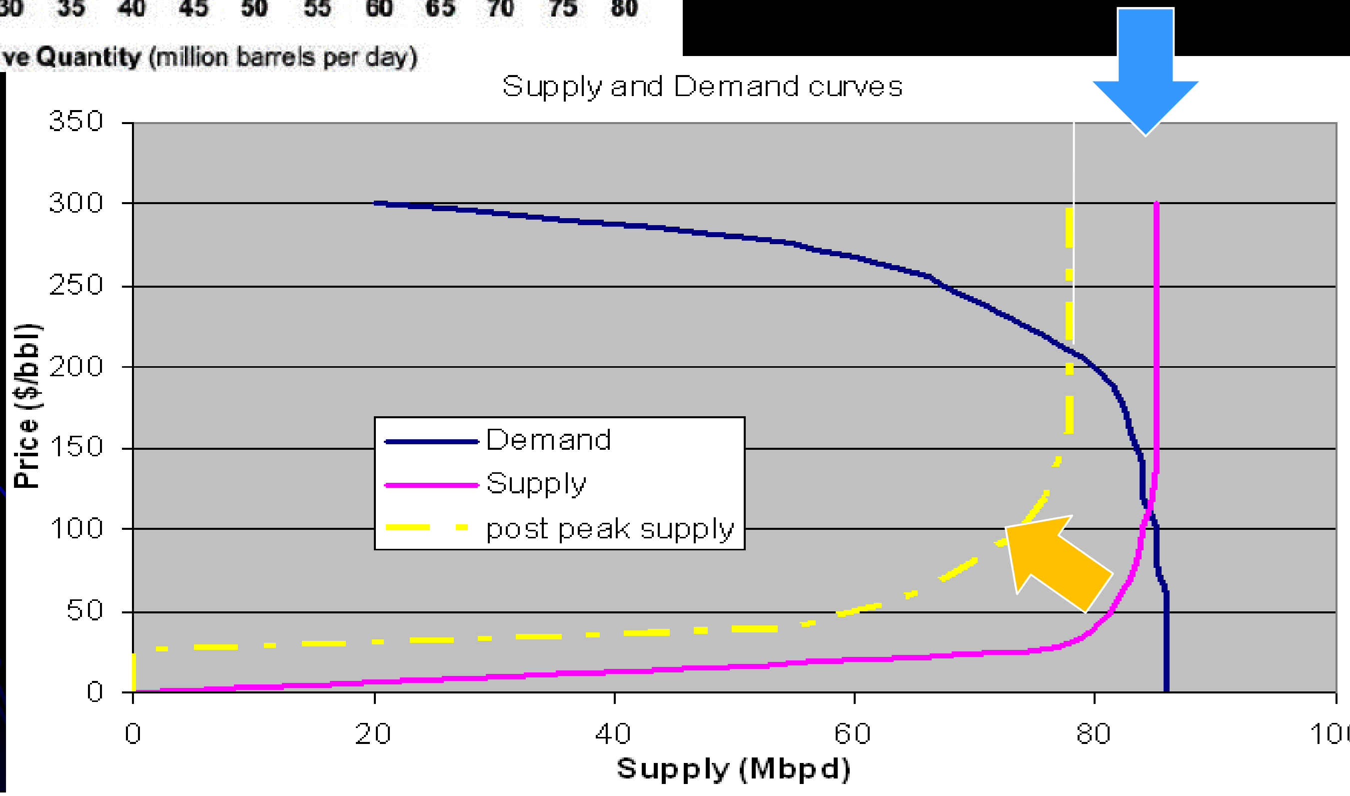
- Financial constraints

What sets oil $ & flow?

- Depleting supply of cheap to produce oil
- Inelastic demand







So many constraints! How to estimate when world flow will decline?

If constraints don't change much …

Hubbert's "curve fitting"

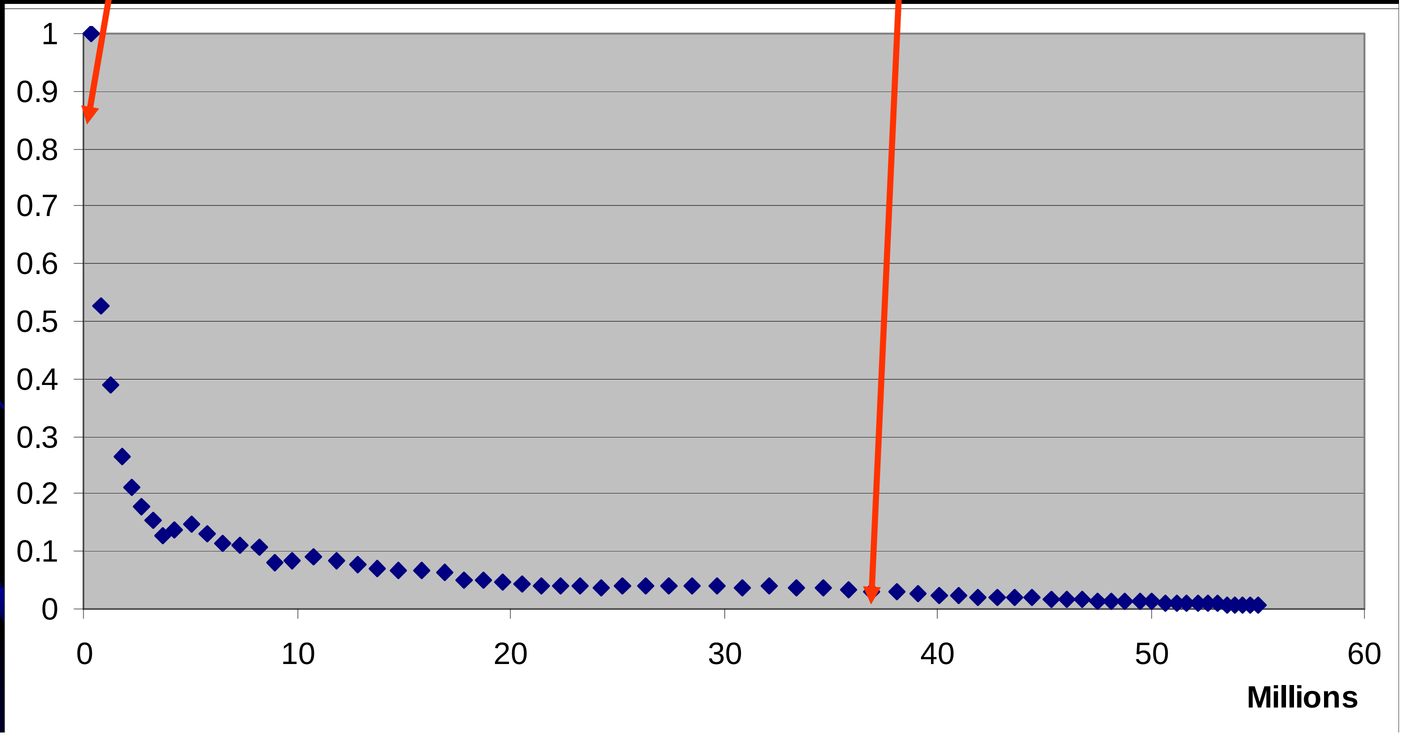
Plot (annual extraction) / (total extracted to date) vs. total extracted to date.

Plot starts at (1st year,1st year), over time drops to (ultimate recoverable, 0)

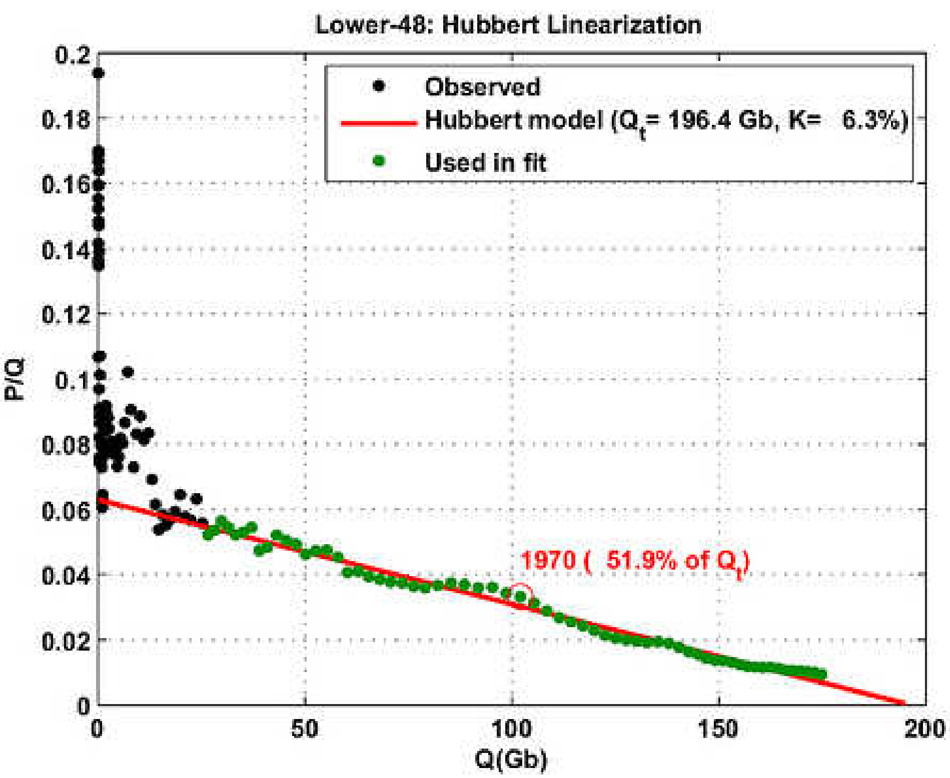
After "noisy" start, curve settles to straight line, so perhaps can extrapolate to predict ultimate (total) recoverable resource (URR) in future

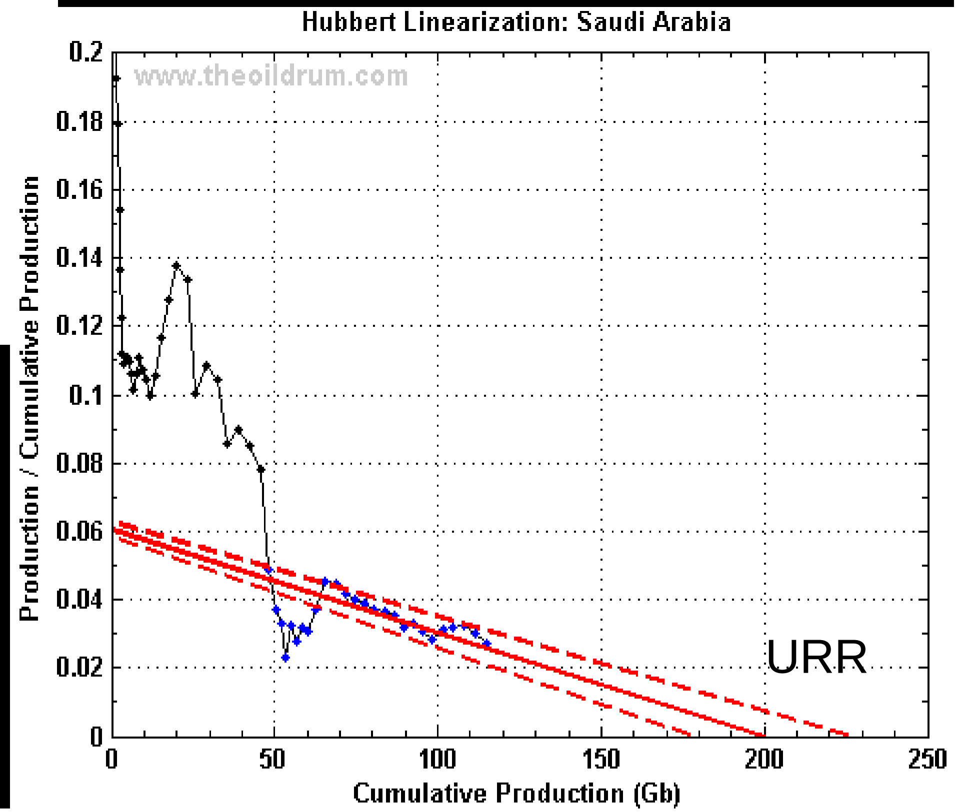
Stepping back halfway approximates year extraction starts to decline (= peak)

Shows that Texas has extracted 90% of all its recoverable oil

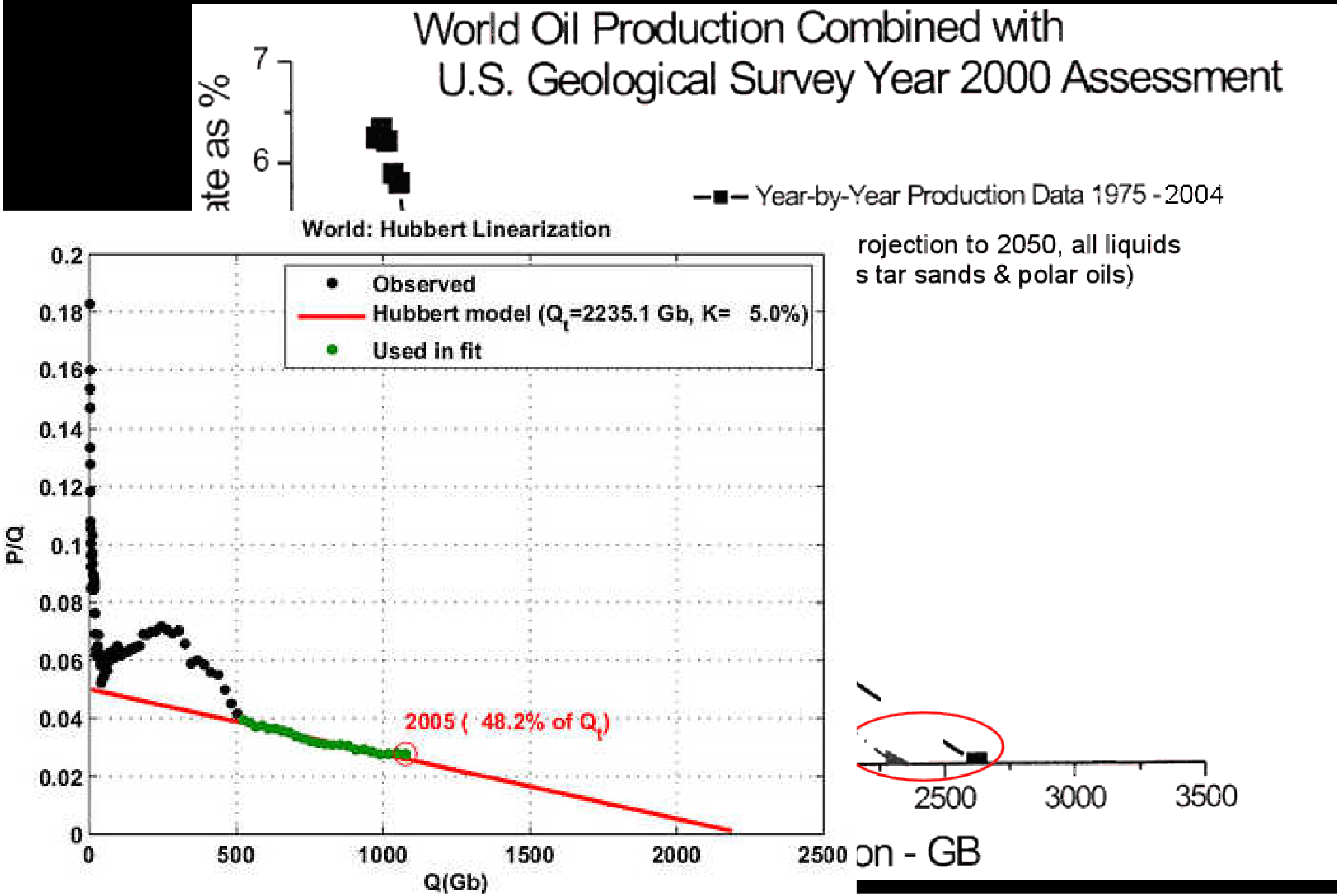


US-48 & Saudi oil histories

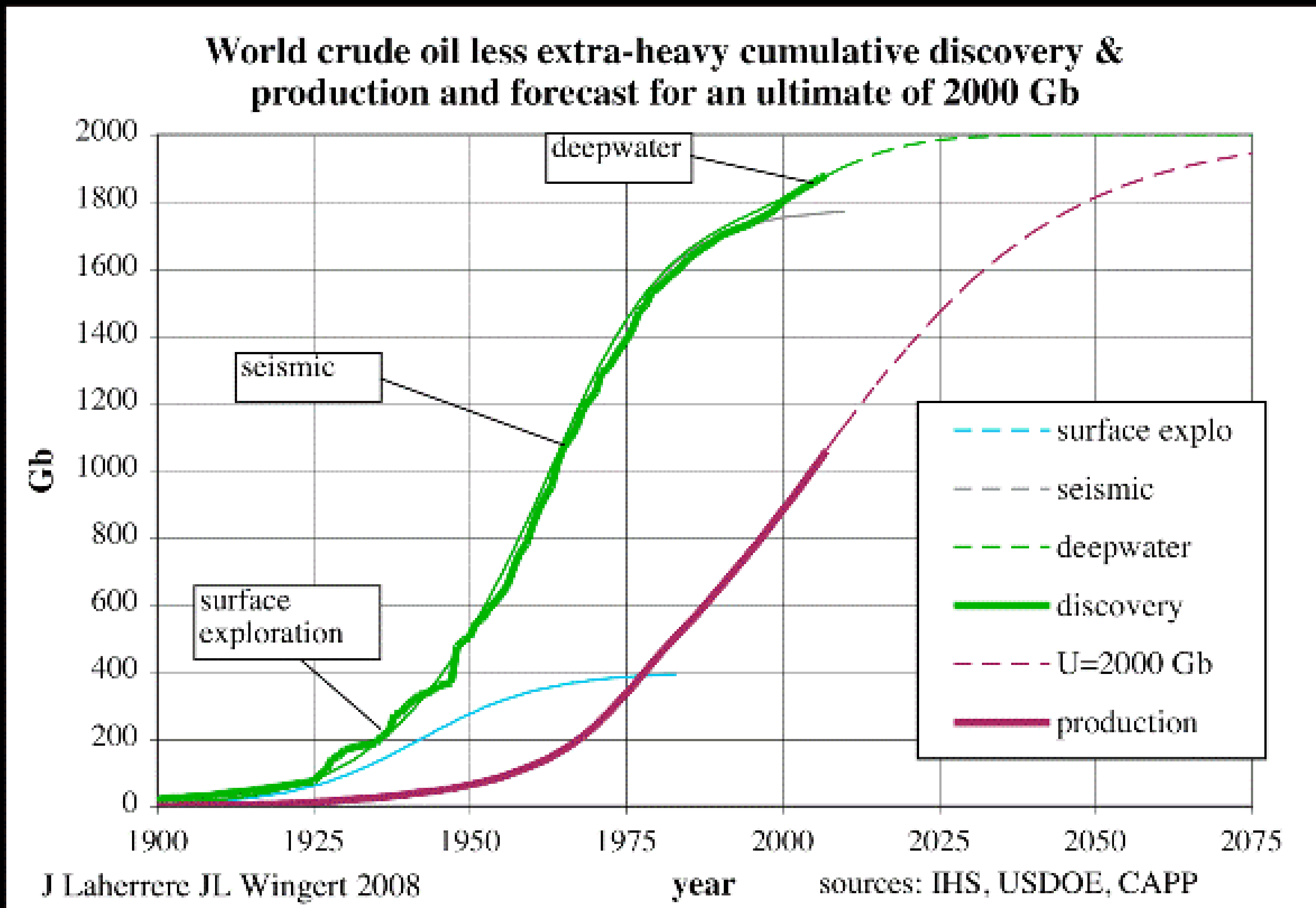




Applied to World Oil Liquids Supply



Result



World crude oil less extra-heavy cumulative discovery &
production and forecast for an ultimate of 2000 Gb
Gb
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1900
1925
1950
1975
2000
2025
2050
2075
deepwater
seismic
surface
exploration
surface explo
seismic
deepwater
discovery
U=2000 Gb
production
J Laherrere JL Wingert 2008
year
sources: IHS, USDOE, CAPP

Apply to coal?

- Too early to be useful, unclear what total Ultimately Recoverable Resource will be

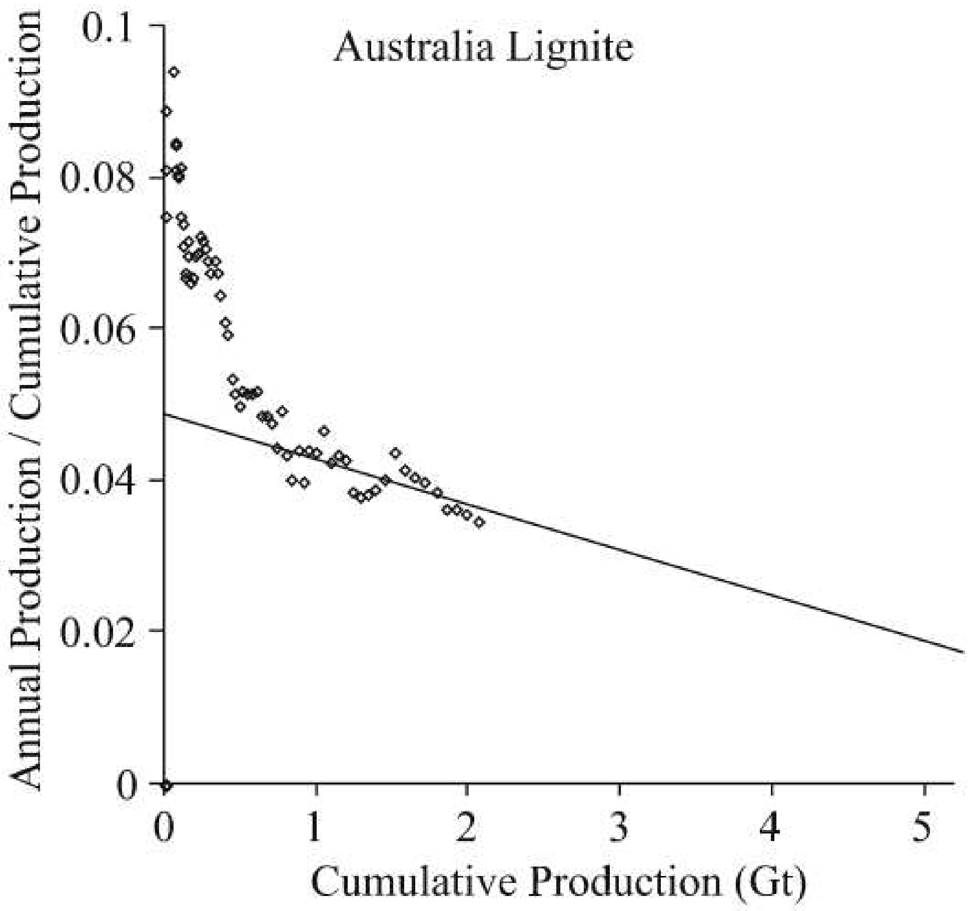
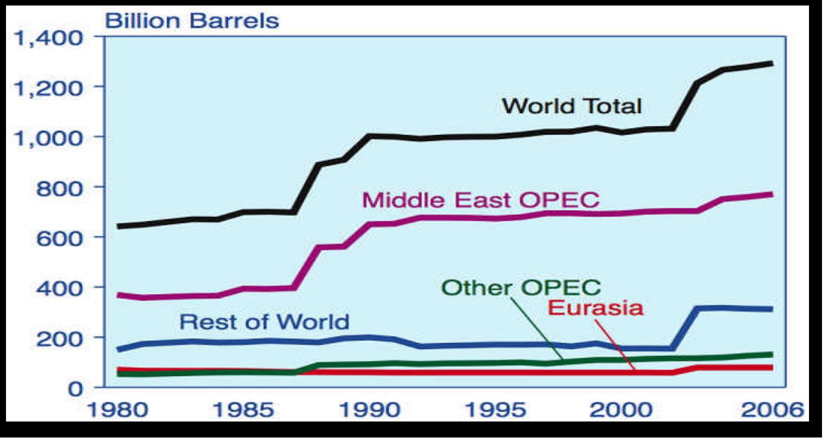


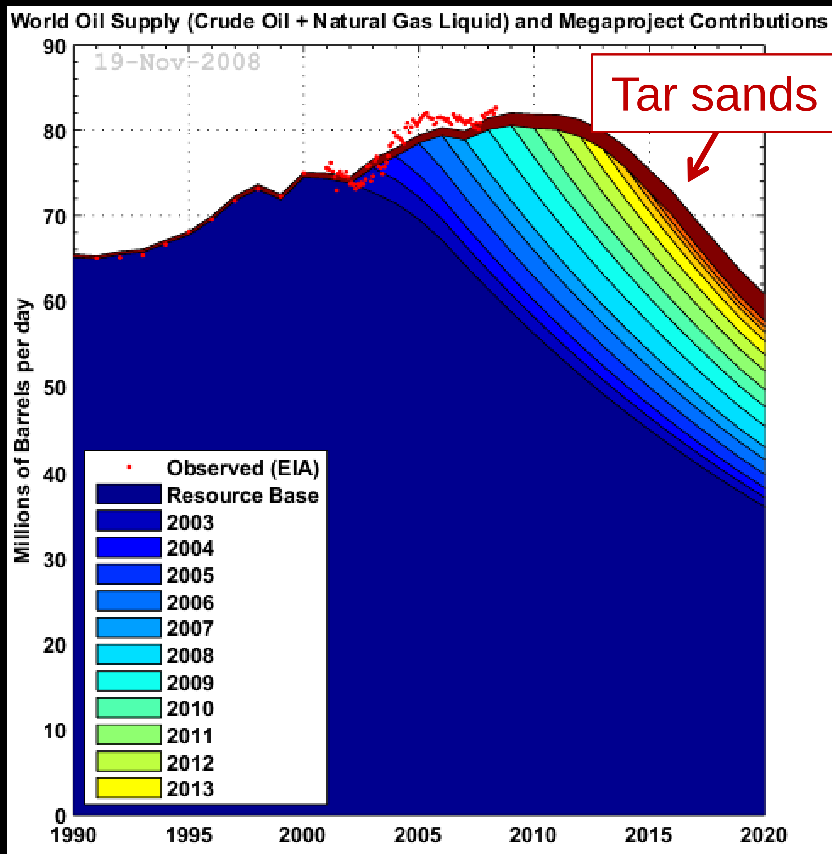
Fig. C.1. The Hubbert Linearisation trend for Australia Lignite.

Peak oil "rolloff timing

- IRRELEVANT: Inflated OPEC reserves or technology?



- FACT: Too few large-volume projects underway to overcome post-2013 depletion



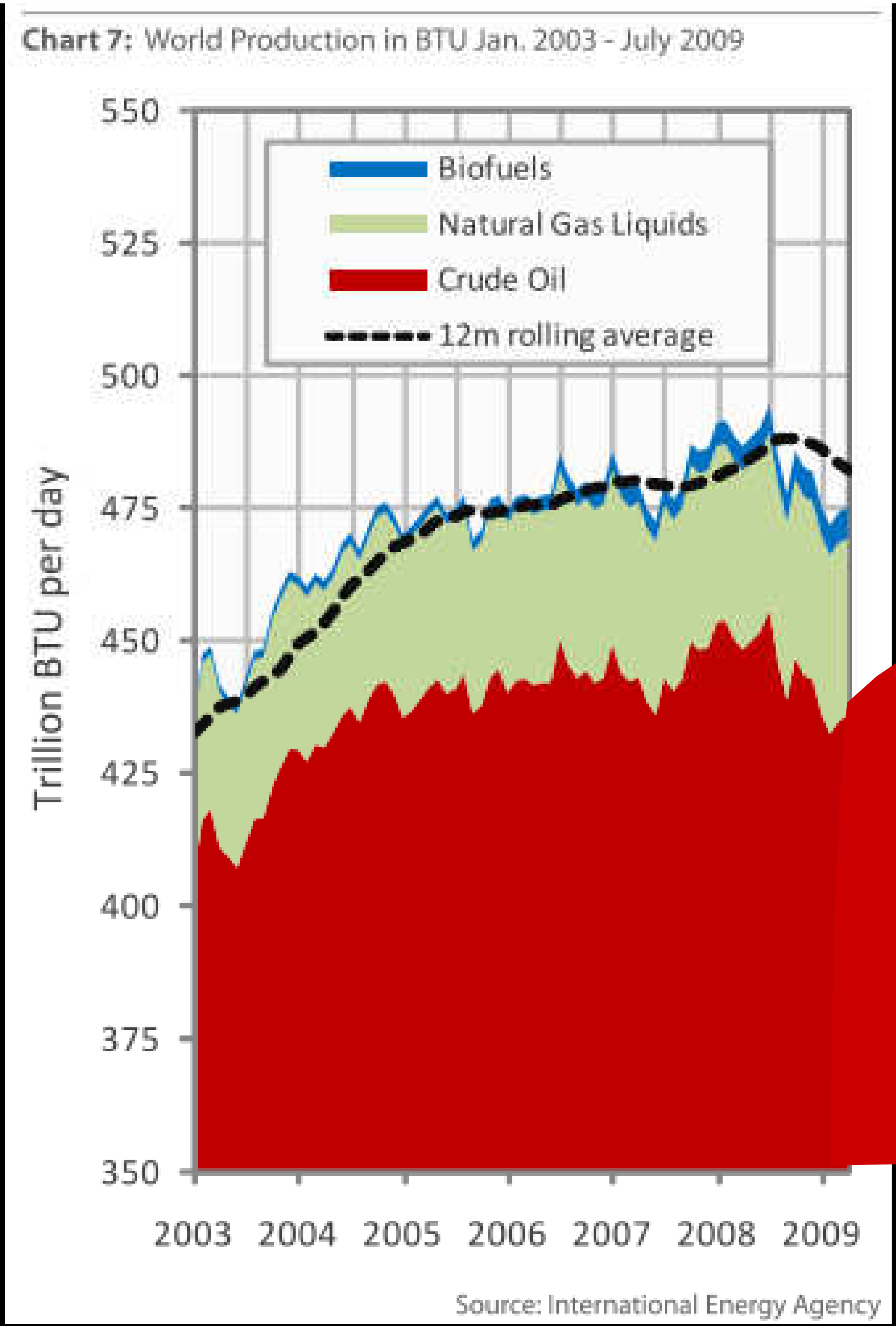
- FACT: New projects tap non-conventional oils, costly & difficult, deliver smaller flows after delays

FACT:

crude oil production has not increased for 5.5 yrs despite high prices until 2 yrs ago

Simplest explanation: Oil flow will no longer grow

When will it decline??



BUT Hubbert "analysis" is only curve fitting, no predictive power, only appeal to precedent. Not science!

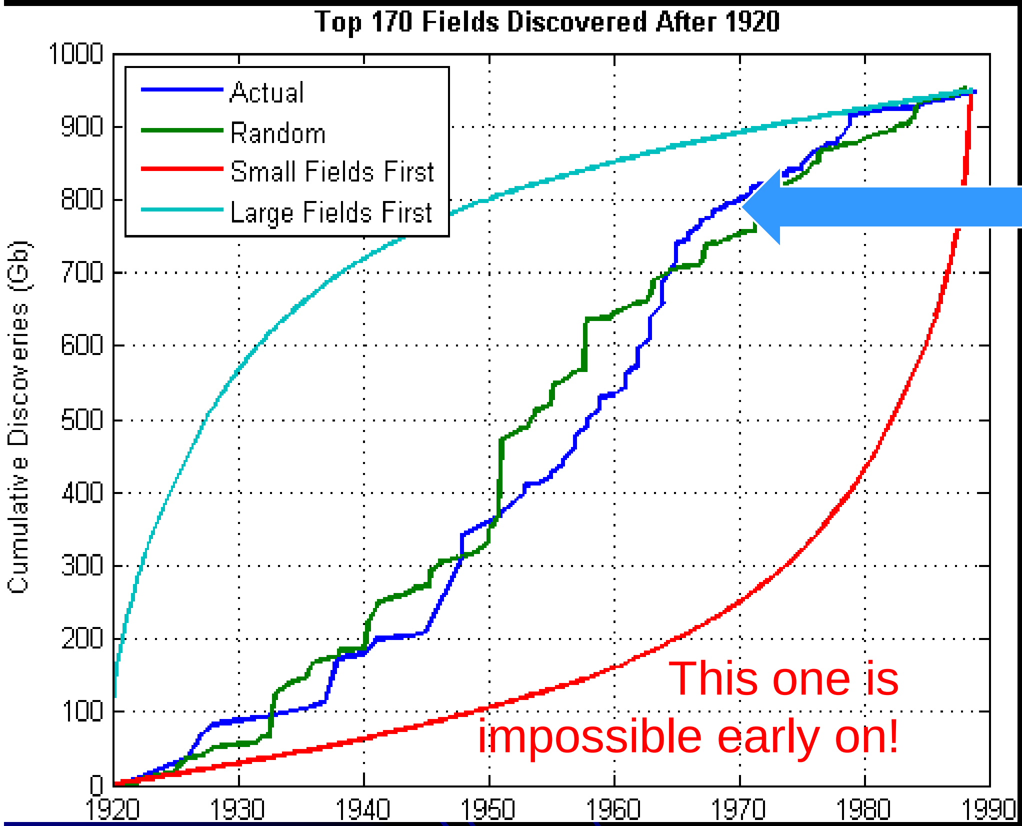
Is there a physical model of oil depletion?

Yes!

First simplification: separate discovery from extraction

Data: volume(time) discovered

Cumulative distribution (= total volume found)



Volume of reservoir is RANDOM … like shoving pipe into ground.

Randomness allows us to use probability distributions effectively.

Sweep a "discovery box" thru depth

of oil-containing spots found by sweeping container volume *L(t)* thru depth *x* follows exponential distribution

$$P(x) = \frac{e^{-x/L}}{L}$$

= constant probability / length (Poisson process).

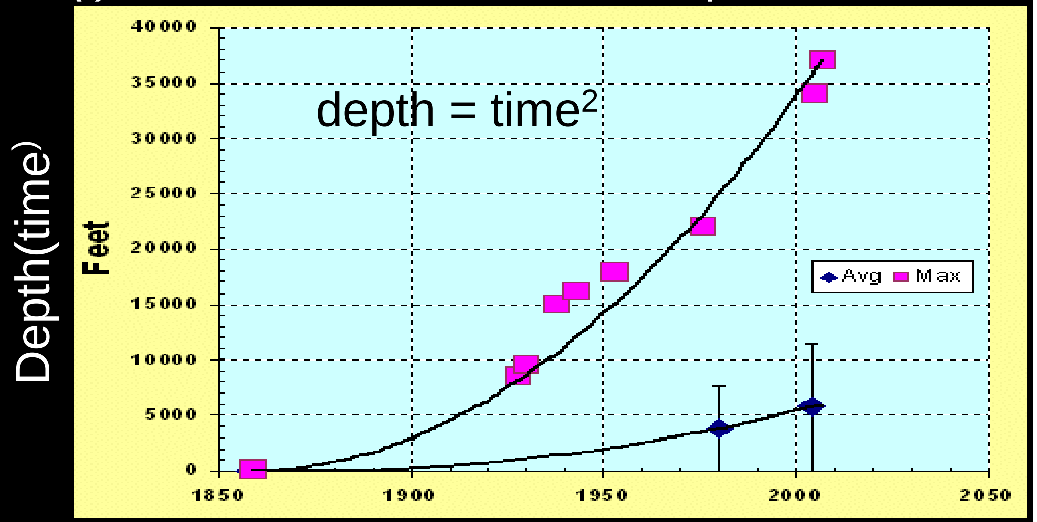
If the reservoir is *V* thick, then average oil discovery depth is

$$N = \int_0^\infty xP(x)dx = L(1 - e^{-V/L})$$

Assuming various exploration factors each increase *L* linearly with time (e.g. # of workers, technology improves), we get …

… cumulative depth(t) of discovered oil

Sweep top to bottom while linearly increasing efficiency(depth) X linearly increasing # of workers(depth). So sweep discovery rate $L(t) = t^2$, and result resembles past US data:

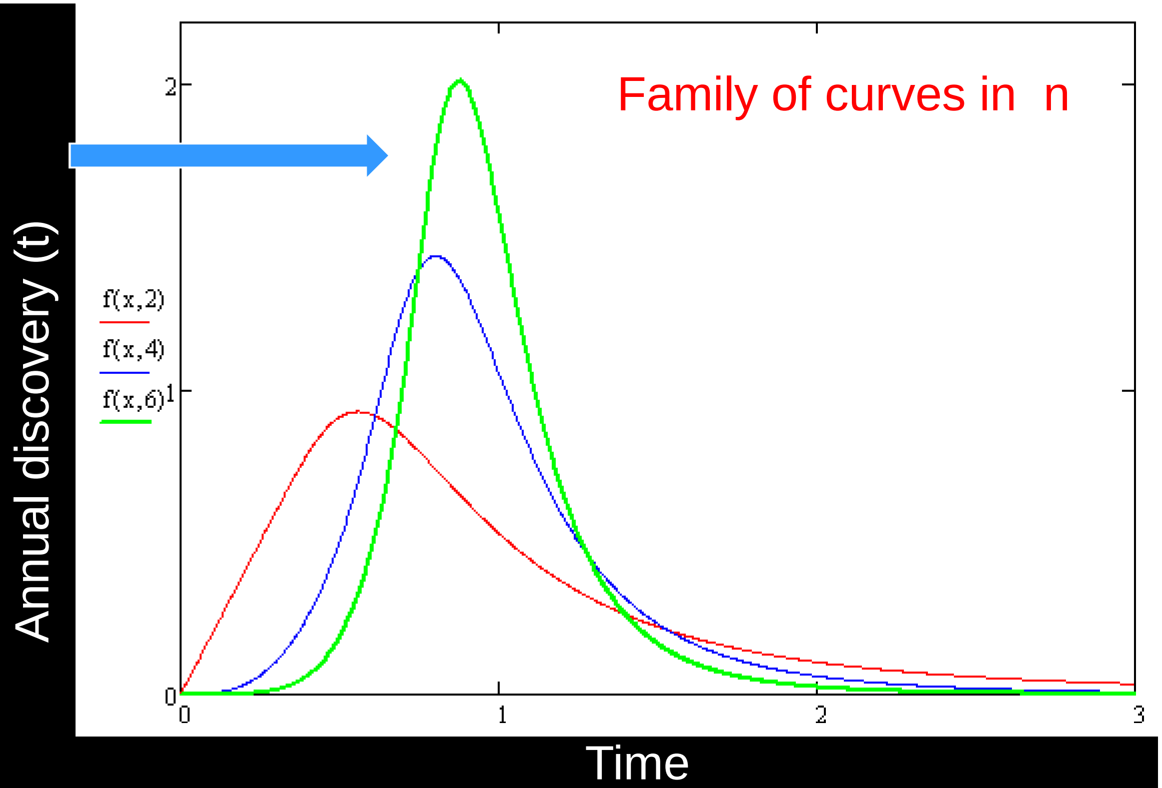


But we search a volume not only depth,
so plausible power is $t^{2+2+2} = t^6$ For general power *n* we have

$$\text{cumulative oil volume} = N = L(1 - e^{-V/L}) = kt^n(1 - e^{-V/kt^n})$$

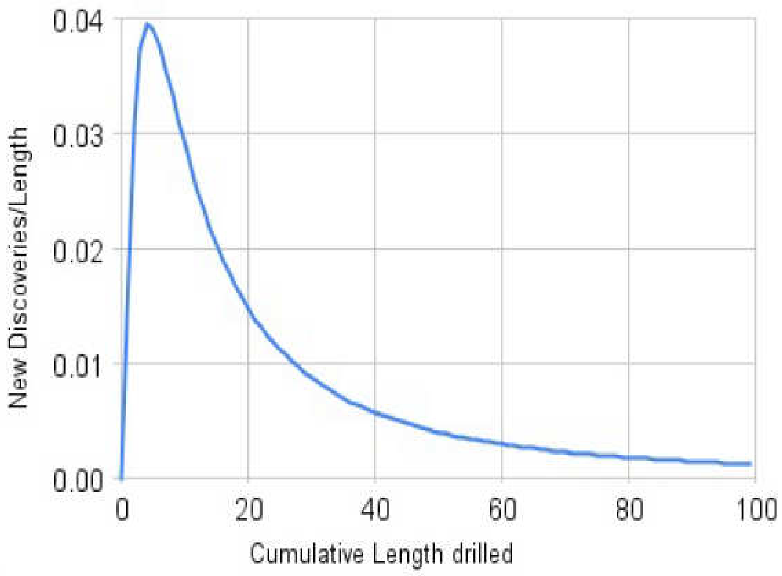
$$\text{annual addition} = \frac{dN}{dt} = nkt^{n-1}(1 - e^{-V/kt^n}(1 + V/kt^n))$$

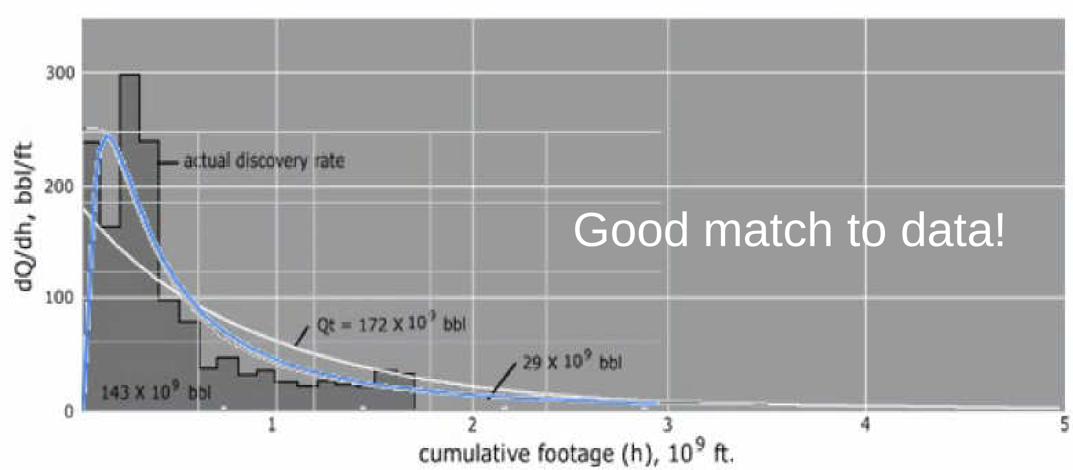
We match US annual addition when *n* = 6



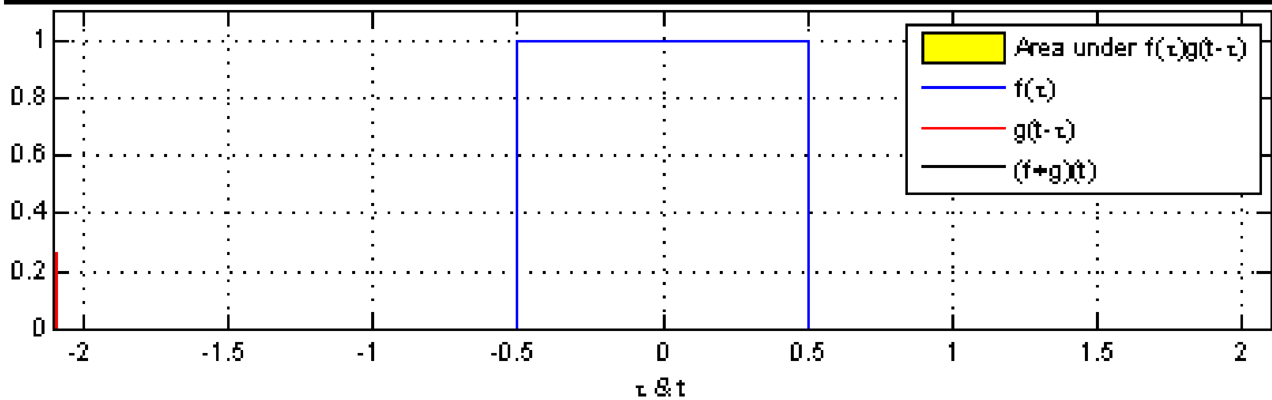
Instead of time on x-axis, here plot related <u>total drill pipe used</u>

US oil discoveries as function of total drill pipe used



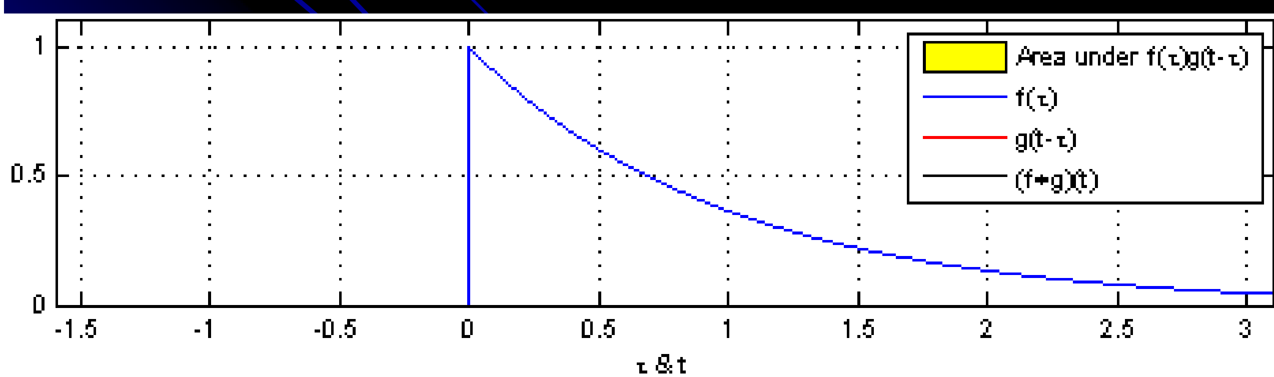


This smoothing is a convolution



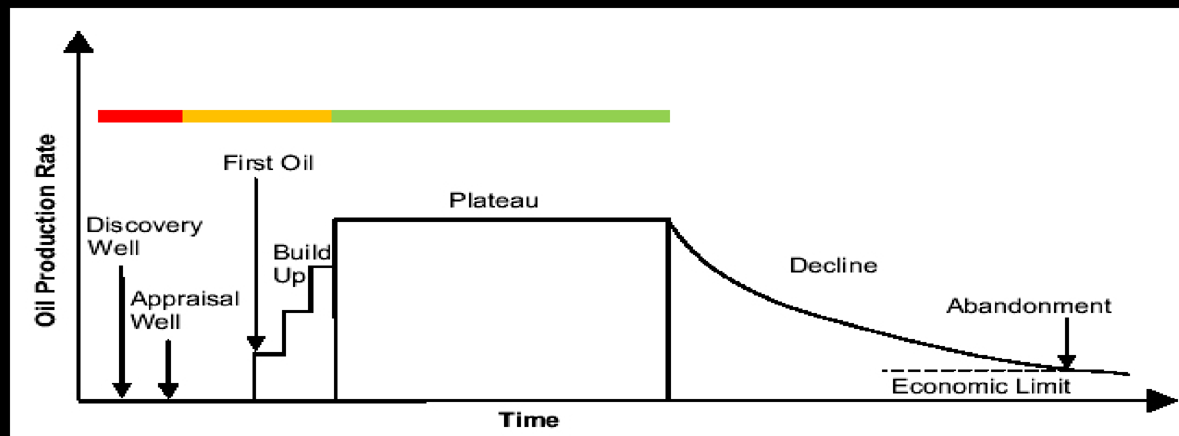
Two distributions, one is viewed thru a window that is slid over other to form weighted average output.

Their instantaneous product (area) is plotted as line, usually smoothing (dispersing) the original distribution.



Reserve Additions

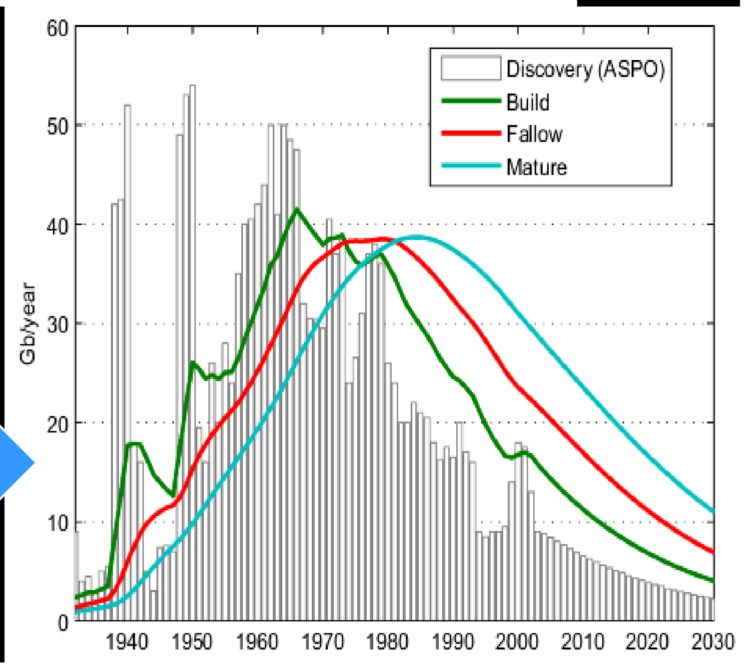
Model: field discovery is dispersed by latency (no field development), then infrastructure construction then full production



We apply a triple convolution of declining exponentials to the field discovery curve *D(t)*

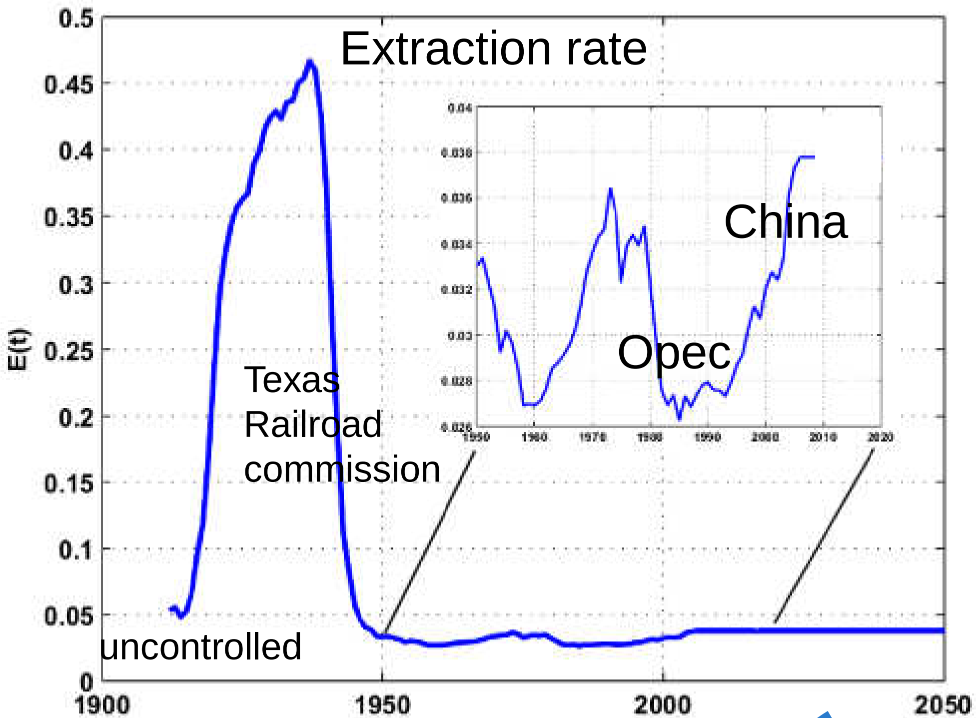
$$(h_{build} \otimes h_{fallow} \otimes h_{mature} \otimes D)(t) = t^2 \frac{e^{-t/\lambda}}{\lambda^3 \Gamma(3)} \otimes D(t)$$

Best fit to data with λ=3 yrs

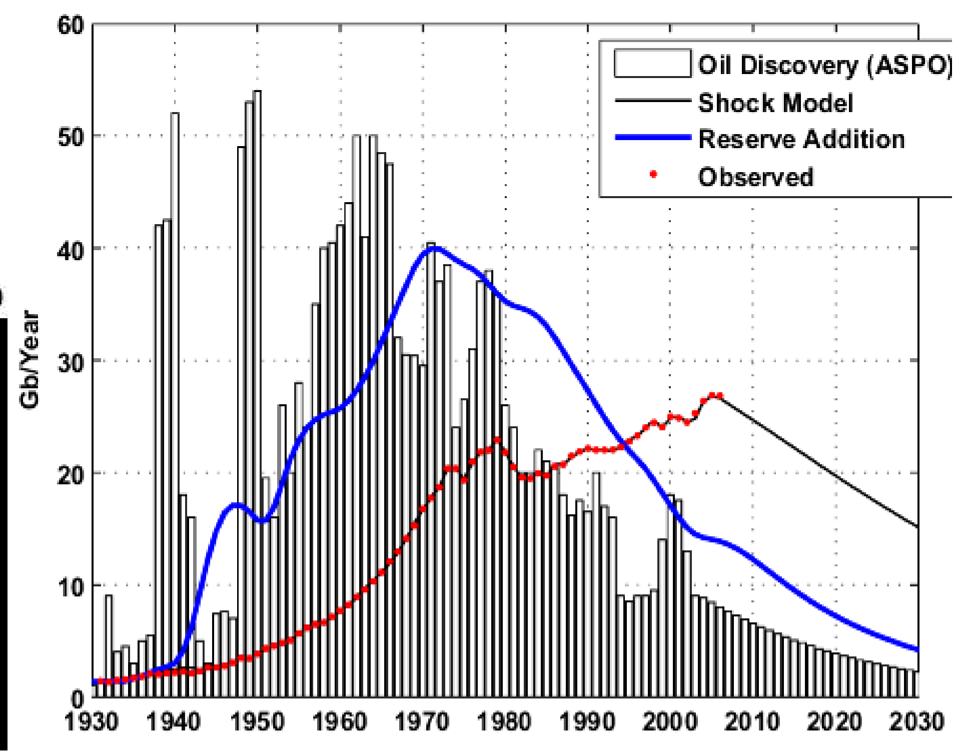


Each successive convolution smoothes *D(t)* more

Multiply reserve additions by an extraction rate



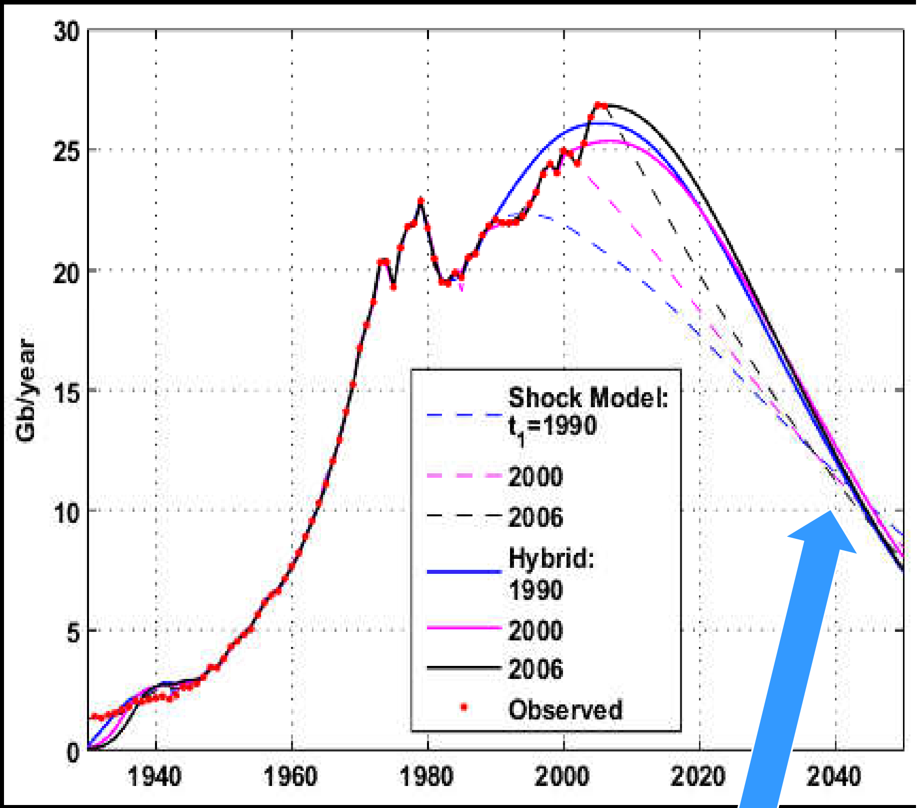
to map discoveries to production



Dynamics of oil production seems to be very simple

A physical model makes testable predictions & gives uncertainties

Work in progress by Foucher et al
(Computer Research Inst. of Montreal)



Apparent convergence
of models because no good
treatment of reserve growth
That will be $$ constrained

Will future resemble the past??

e.g. assume constant shock rate in future :

Note: all projections
from past rates converge

Our oil future depends on potential for reserve growth

= reported reservoir estimate improves over time from

1) Drilling marginal wells to better define reservoir volume

2) Advanced tech to increase flow

3) Mergers & Acquisitions adjust financial reporting rules (country specific).

All murkier in past than today.

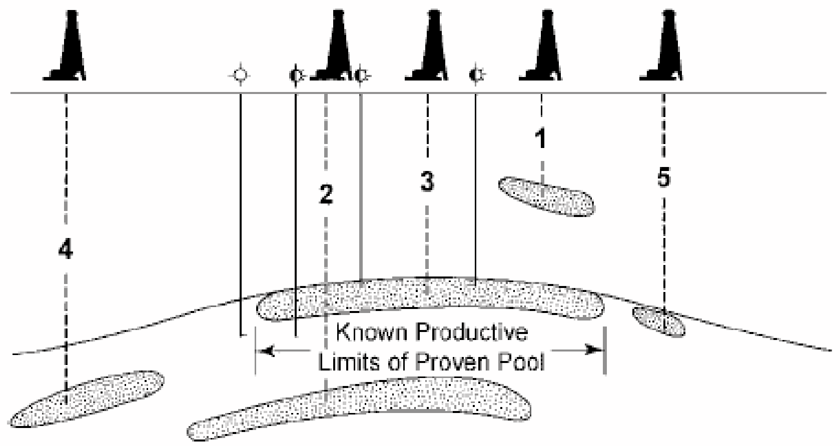
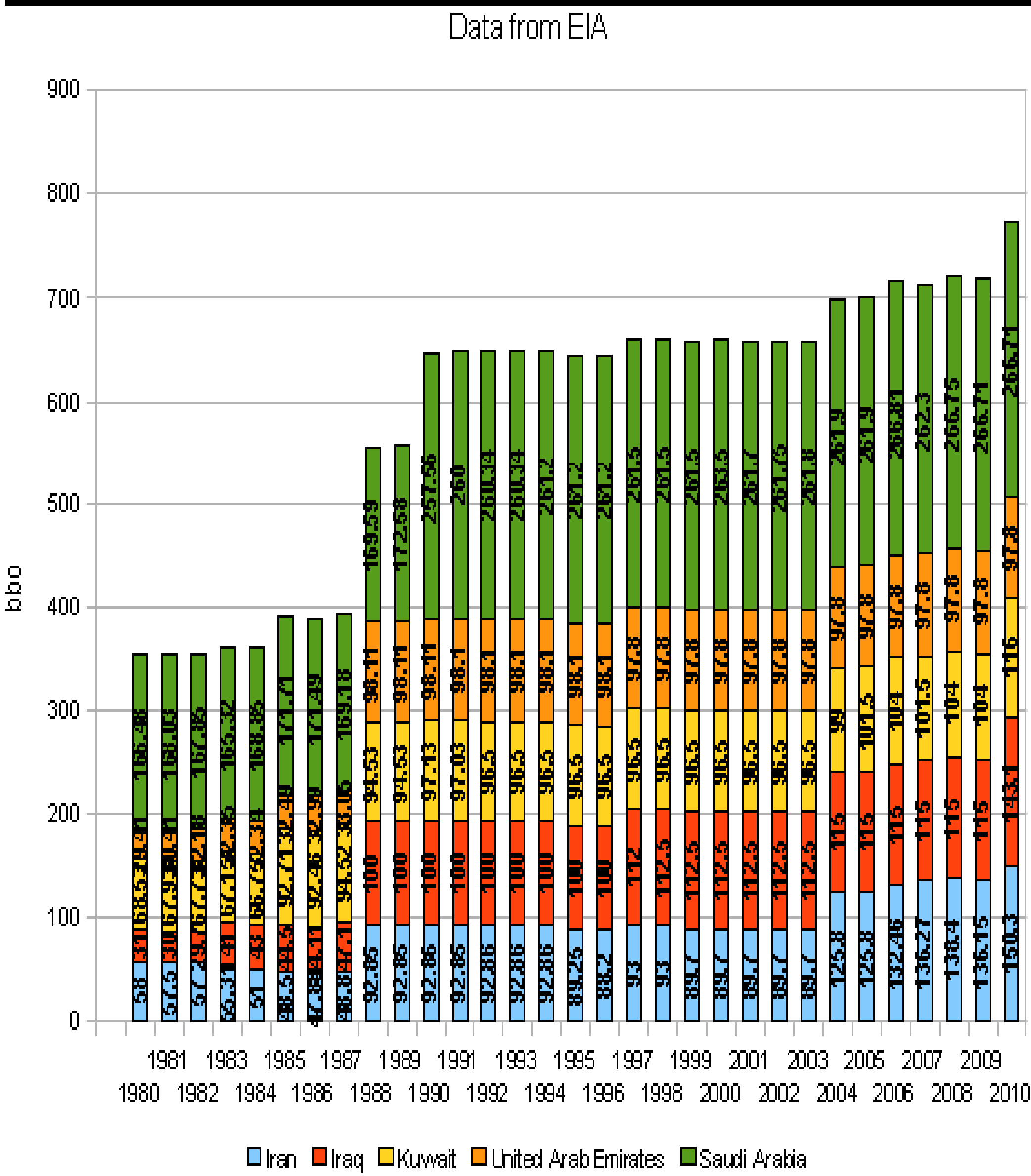


Figure 1. Schematic wells leading to additions to reserves in discovered fields; (1) shallower pool test, (2) deeper pool test, (3) infill well, (4) new pool test, (5) extension or outpost (modified from Drew, 1997). In practice, an operator or regulatory body may classify accumulations penetrated by wells 1 through 5 as a single field or as more than one field. Recognition of the relationship among accumulations also could be complicated further by the order in which wells were actually drilled.

1) & 2) do not increase total
- 5% boost from tech delays Peak Oil by 5 yrs but tech increases flow not total

3) masks the oil decline !

Fake reserve growth?



- National oil Co have 80% world oil reserves
  - Self report their reserves
  - indep. check is $$$$
- OPEC country quota is set by its oil reserves
  - Can sell % of remainder
  - Mysterious increases
    - No new discoveries
    - Attracts investment
- USGS attributed such “growth” just to tech
  - Boosts global reserves

Field-by-field depletion would tell us the whole PO story

- That governments have not demanded these data from ME suppliers is telling
- Numbers provided to date are very suspicious
- There are no published contingency plans for oil shortages
- US strategic petroleum reserve holds 20 days of full use crude oil -> rationing
- We remain vulnerable to “oil shock” supply disruptions, and especially refinery sabotage