Growth & Decline of Resource Use

Understanding exponential growth

Exponential vs linear growth
overshoot
stocks vs flows
models
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 x 1.085^{50})
Whoa, where’d all that come from!??

Boringly predictable, slow politics/policies agrarian society

Barely perceptible early growth

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

Malthus: food area grows linearly, population exponentially
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

\[ t = 1 \]

\[ 31/31 \]

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.

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

e.g. told that resource will last 300 yr if consumed at present rate

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

---

CAUTION
- Wellhead oil and gas
- Processing oil and gas
- Pipelines and tankers
- Drilling rigs
- Refinery capacity
- People, people, people...
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 …
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
- Abrupt climate change mid-1990s CO₂
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
- Ehrlich: The Population Bomb
- Pimentel & Odum: quantified energy inputs in agriculture
Late 1960s

- **Club of Rome**
  - 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)
Start of Systems Dynamics
Model exponential & linear interactions
Rediscovered overshoot dynamics evident in animal populations

Feedback loops

Feedback Loops for Population, Capital, Agriculture, & Pollution [Beyond the Limits]
Feedback Loops for Population, Capital, Services, & Resources [Beyond the Limits]
Evolving studies of Limits of Growth

- **Note:** LoG has been completely dismissed by mainstream (1980 Ehrlich/Simon bet)

  - *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

State of the World

Material standard of living

Energy usage

Click on the SyntheSun Icon and move sliders to see what changes
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
Currently, a minor impact on efficiency compared to engineering
Energy conversions

In practice
Recall: 1st Law Thermodynamics

\[ Q = \Delta U + W \]

Heat In \[ \rightarrow \] Change of Internal energy (T rise and/or phase change) \[ + \] Mechanical work done

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

Working fluid

Boil cold water into steam

Expand steam on turbine blades

$W_{\text{turbine}}$

$Q_{\text{boil}}$

$W_{\text{pump}}$

Condense steam to water

Pump water

Minimize this for Maximum efficiency

Around cycle $\Delta u = 0$ so 

\[(Q_{\text{boil}} - Q_{\text{condense}}) - (W_{\text{turbine}} - W_{\text{pump}}) = 0\]

Therefore

\[
\text{efficiency} = \frac{\text{net work out}}{\text{heat input}} = \frac{W_{\text{turbine}} - W_{\text{pump}}}{Q_{\text{boil}}} = \frac{Q_{\text{boil}} - Q_{\text{condense}}}{Q_{\text{boil}}} = 1 - \frac{Q_{\text{condense}}}{Q_{\text{boil}}}
\]
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 $Q_{\text{condense}}$ is released into environment
- Hence, efficiency $= 1 - \frac{Q_{\text{condense}}}{Q_{\text{boil}}} < 1$
Most efficient work from burning fuel is (Carnot)

\[ \varepsilon_{\text{max}} = \frac{\text{Max work out}}{\text{Energy in}} = \frac{T_H - T_L}{T_H} = 1 - \frac{T_L}{T_H} \]

\( T_H \) and \( T_L \) are working fluid temps in K

**Burning** fuel CANNOT BEAT this limit

e.g. wood stove \( T_H = 300^\circ C + 273 = 573 K \)
ejects to \( 5^\circ C + 273 = 278 K \)

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\cdot0.51 = 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 (soften at $T_H$, typical turbine $565\,^\circ C$)
- Environment (at $T_L$, typical $30\,^\circ C$)
Practical engine cycles 1-4

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

Faster cycle = more power out

“cut corners” so reducing efficiency
Power & efficiency are opposites!

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.

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

\[ \varepsilon_{\text{power plant}} = \varepsilon_{\text{boiler}}\varepsilon_{\text{turbine}}\varepsilon_{\text{generator}} \]

\[ = \left( \frac{\text{Thermal}}{\text{Chemical}} \right) \left( \frac{\text{Mechanical}}{\text{Thermal}} \right) \left( \frac{\text{Electric}}{\text{Mechanical}} \right) = \left( \frac{\text{Electric}}{\text{Chemical}} \right) \]

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

Entropy dumped here or here
Now, heat your home most efficiently

1) Using electricity from distant power plant:

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

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

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

2) Using heat from home furnace:

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

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

\[
\varepsilon_{\text{NG}} = \varepsilon_{\text{extraction}} \varepsilon_{\text{processing}} \varepsilon_{\text{transport}} \varepsilon_{\text{furnace}} = (0.73) (0.97) (0.95) (0.92) = 0.62 (62 \text{ percent})
\]
Clean up coal, only 5% hit on output power. Add CO$_2$ control, get 20% more hit.
Combined Gas turbine

Gas turbine

Combined Gas + steam turbines + cogeneration
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 \( \degree \)C in common units. Works best in moderate climate SC
- Ground source: in NC 1 ft into soil \( T_L \sim 15 \degree \)C — 288.8 \( \text{K} \)
Ground loop & air loop heat pumps

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

adequate to power all of humanity if not for CO$_2$

Decline ~2014  Decline ~2030?  Peaking ~2030?
Figure 5.4: The carbon cycle quantitatively (units are $10^{12}$ kg of carbon stored and $10^{12}$/yr transferred), showing the relatively small but critical human component in the context of the whole cycle.
Global Carbon Cycle

Diagram:
- Carbon Dioxide in Water
- Carbon Dioxide in Atmosphere
- Carbon Dioxide in Rocks
- Plants
- Animals
- Dead Plants/Dead Animals
- Fossil Fuels

Processes:
- Photosynthesis
- Decay
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$_2$O → C$_6$H$_{12}$O$_6$+6O$_2$
    - Energy is held in C-C & C-O & C-H electron bonds
- Cycle completes by aerobic decay (oxidation)
  - C$_6$H$_{12}$O$_6$+6O$_2$ → 6CO$_2$+6H$_2$O + 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

Paleocene (55-45 My)
Today SE Asia, N. of Australia making oil ready 10s Myr from now
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 $T + \text{water}$ 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 @ $T = 60-120 \, ^\circ C$: 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 write-off)
  - 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/CO₂
- Finally remove NG cap, stranding 30-40% OIP
Draining Oil/NG Field

Dying

Extract gas cap, rapid decline (20%/yr), field dead

Water

Gas

Gas

Stranded Oil

Brine

Production, BOPD x 1000

Enhanced oil production at Weyburn

CO₂
Another example

**MEXICO:** Daily production from one-time super-giant "Cantarell" oilfield 000 b/d

- Nitrogen injection
- Collapse

Source: Energy Information System, Federal Government of Mexico
Printed: 27/07/2009
Deep Discovery

Drilling in waters up to two miles deep, oil companies are making some very large discoveries. The first test of whether oil would flow from these ultra-deep wells, at Chevron’s Jack well, was successful.

### Water Depth (feet)

<table>
<thead>
<tr>
<th>Operator</th>
<th>Prospect Name</th>
<th>Water Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petrobras/Devon</td>
<td>Cascade</td>
<td>8,143</td>
</tr>
<tr>
<td>Petrobras</td>
<td>Chinook</td>
<td>8,831</td>
</tr>
<tr>
<td>BP</td>
<td>Kaskida</td>
<td>6,860</td>
</tr>
<tr>
<td>Chevron</td>
<td>Trident</td>
<td>9,743</td>
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<tr>
<td></td>
<td>Tobago</td>
<td>9,627</td>
</tr>
<tr>
<td></td>
<td>Silvertip</td>
<td>9,226</td>
</tr>
<tr>
<td></td>
<td>Tiger</td>
<td>9,004</td>
</tr>
<tr>
<td></td>
<td>St. Malo</td>
<td>7,036</td>
</tr>
<tr>
<td></td>
<td>Jack</td>
<td>6,965</td>
</tr>
<tr>
<td>Shell</td>
<td>Stones</td>
<td>9,556</td>
</tr>
<tr>
<td></td>
<td>Great White</td>
<td>8,717</td>
</tr>
</tbody>
</table>

Source: Minerals Management Service

Scale varies in this pental. Flows the Mississippi to New Orleans is 316.1 miles (513 km). Source: U.S. Department of the Interior and National Geographic Maps.
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

Very reactive 2 & 3 bonds

“A100 octane” cut with n-heptane

2,2,4-Trimethylpentane (also called isoctane), present in gasoline has an octane number of 100 and is used as a standard for octane rating. Gasoline contains mostly branched hydrocarbons with 3 to 10 carbon atoms, which have high octane rating. Straight chain n-octane in contrast, is completely unsuited as a gasoline fuel with an octane number of -19

n-Hexadecane (C16H34), a substance that has the ability to self-ignite quickly in Diesel motors was given a cetane number of 100 and is used as a standard for cetane rating. Diesel fuel contains mainly straight chain alkanes with 10 to 20 carbon atoms.
Oil Refining

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

- **Vaporize** crude oil @ 700 °F
  - 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

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

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

<table>
<thead>
<tr>
<th>Product</th>
<th>Main use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gases</td>
<td>Industrial &amp; residential fuel</td>
</tr>
<tr>
<td>Gasoline</td>
<td>Fuel in spark-ignition engines</td>
</tr>
<tr>
<td>Diesel fuel</td>
<td>Fuel in compression-ignition engines</td>
</tr>
<tr>
<td>Jet fuel (Kerosene)</td>
<td>Fuel for jet engines &amp; gas turbines</td>
</tr>
<tr>
<td>Fuel oils</td>
<td>Industrial or residential fuel</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
<th>Color</th>
<th>Calorific value (BTU/gallon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Kerosene</td>
<td>Light</td>
<td>137,000</td>
</tr>
<tr>
<td>2</td>
<td>Distillate</td>
<td>Amber</td>
<td>141,000</td>
</tr>
<tr>
<td>4</td>
<td>Very light residual</td>
<td>Black</td>
<td>146,000</td>
</tr>
<tr>
<td>5</td>
<td>Light residual</td>
<td>Black</td>
<td>148,000</td>
</tr>
<tr>
<td>6</td>
<td>“Residual (Bunker C)”</td>
<td>Black</td>
<td>150,000</td>
</tr>
</tbody>
</table>
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 refineries (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

CERA
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 (1\text{st} year,1\text{st} year), over time drops to (ultimate recoverable, 0)

After “noisy” start, curve settles to straight line, so perhaps can \textit{extrapolate} to predict \textit{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

World Oil Production Combined with U.S. Geological Survey Year 2000 Assessment

- Year-by-Year Production Data 1975 - 2004

Projection to 2050, all liquids (tar sands & polar oils)
Result

World crude oil less extra-heavy cumulative discovery & production and forecast for an ultimate of 2000 Gb

J Laherrere JL Wingert 2008

Sources: IHS, USDOE, CAPP
Apply to coal?

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

$$depth = time^2$$

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

For general power $n$ we have

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

$$annual \ addition = \frac{dN}{dt} = nkt^{n-1} (1 - e^{-V/kt^n} (1 + V / kt^n))$$
We match US annual addition when $n = 6$

Instead of time on x-axis, here plot related total drill pipe used.

US oil discoveries as function of total drill pipe used.

Good match to data!
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 $D(t)$:

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

Best fit to data with $\lambda = 3$ yrs

Each successive convolution smooths $D(t)$ 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.

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!

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**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.
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