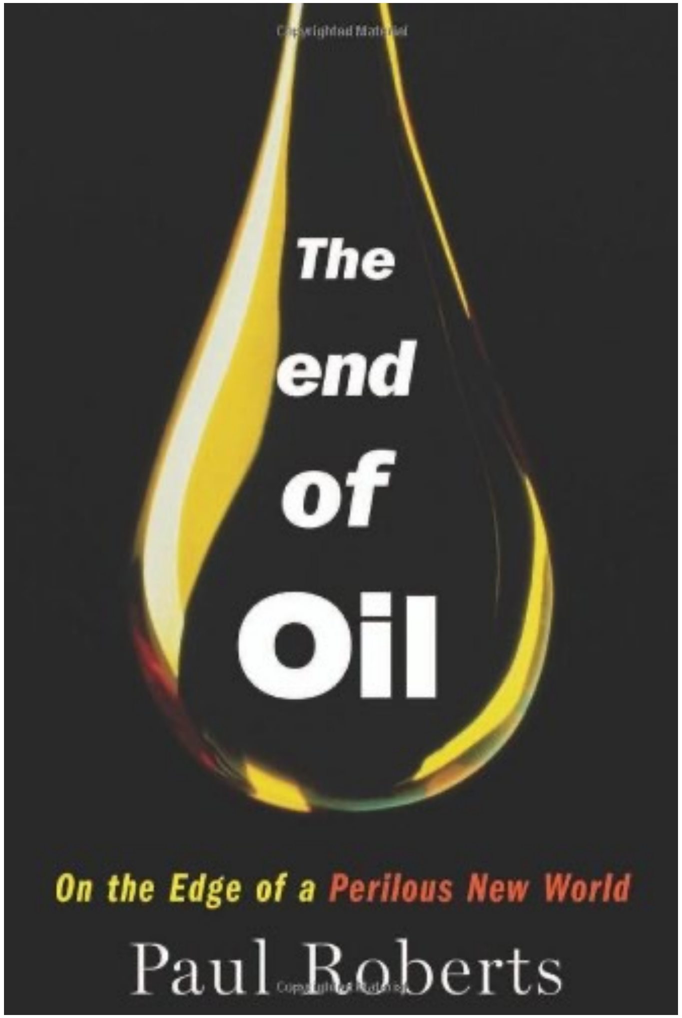
Nonrenewable Resources

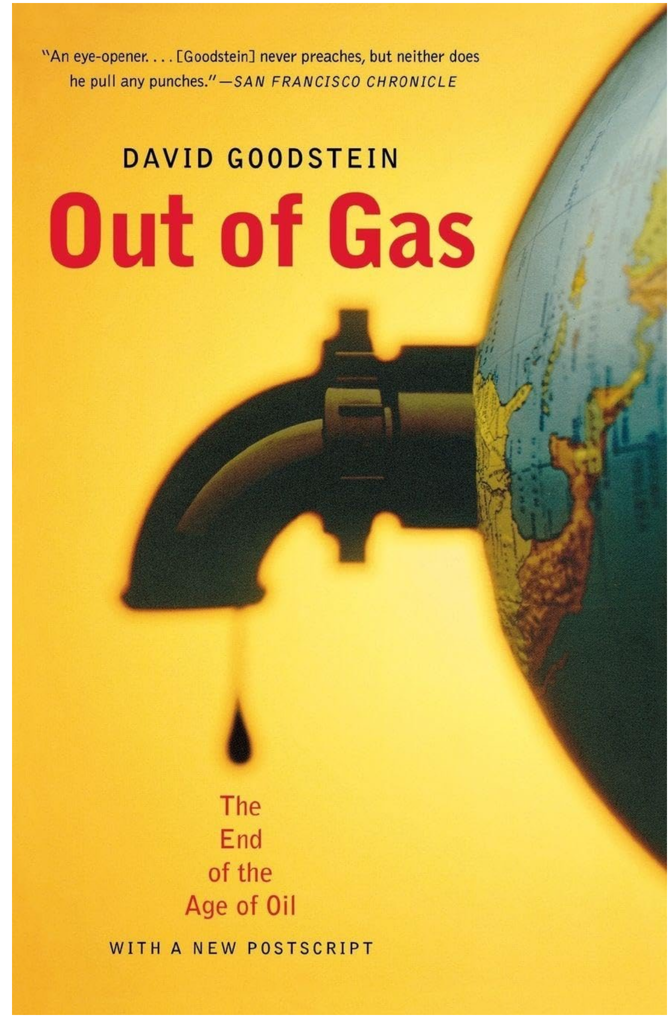
Dynamic Efficiency, Markets, & Market Failure

Prof. Richard Sweeney
Econ 3391

Adapted from:
Harvard API-135/Econ 1661
Professor Robert Stavins

The supply of fossil fuels is inherently finite





This has important implications for how we think about efficient consumption and environmental policy in these markets.

Outline for today

- Go over a simple 2 period model model of nonrenewable resource extraction
  - Gives almost all the intuition for how to think about dynamic efficiency in fossil fuel markets
  - N-period results in backup for those interested
- Use this model to understand what an economically efficient price looks like
  - Compare to the condition you learned in econ 101
- Then use it to discuss implications for climate policy
  - Homework → to be discussed next class

Economics of nonrenewable resources

Examples: fossil fuels and other minerals such as lithium, germanium, cobalt (which are essential for energy transition + AI boom)

Question: How fast should a nonrenewable resource be extracted?

What does efficiency mean in this context?

- MB = MC
- Where MC includes **opportunity cost**

Nonrenewable resources involve a specific opportunity cost

- If you use a good today, it is not available tomorrow

The dynamically efficient rate maximizes the present value of future net benefits (surplus)

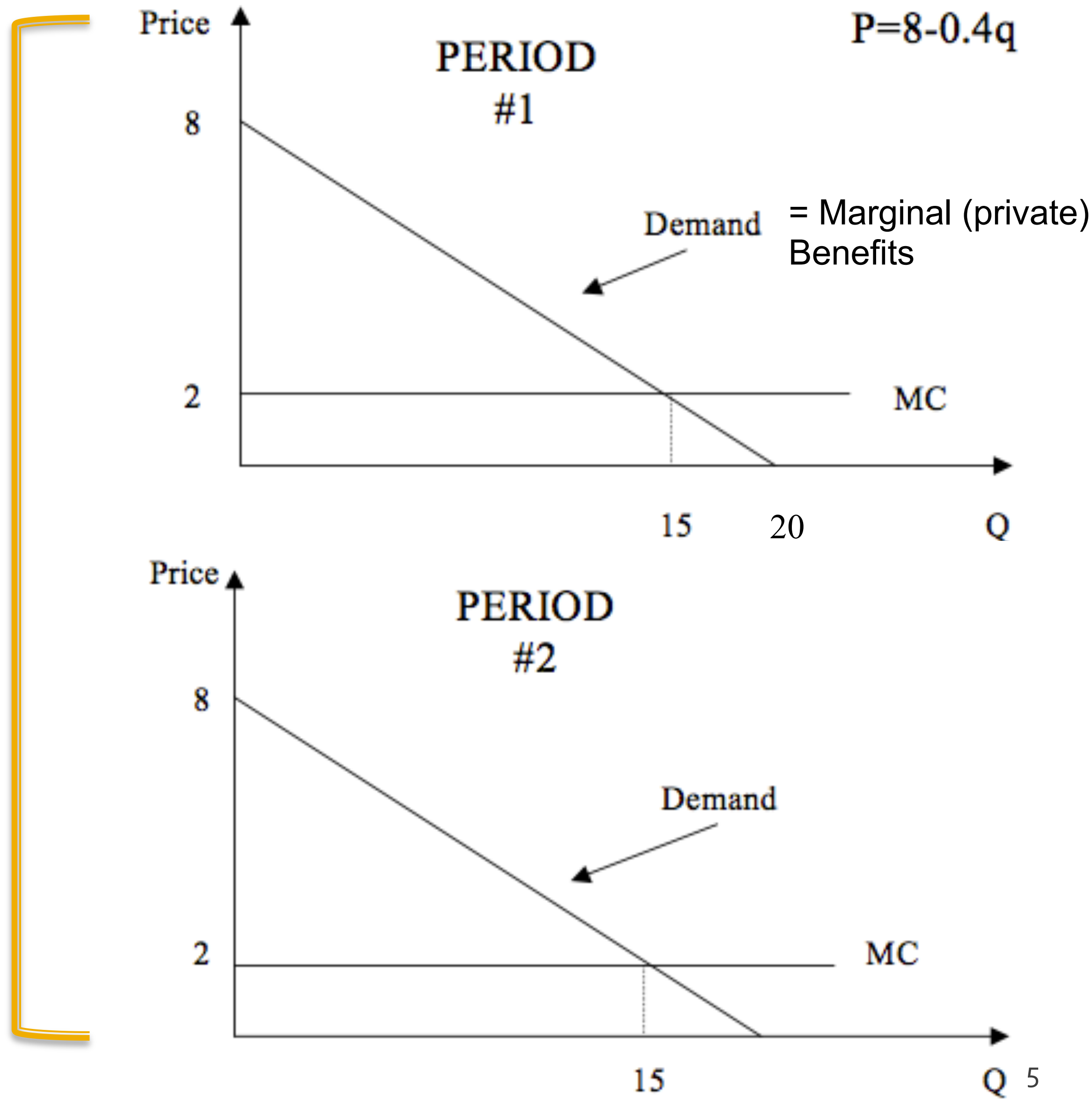
Insights from a simple two period model

- Let's look at this a bit more rigorously in a simple two-period model
    - ie "today" and "the future"
- Put aside environmental externalities, other market failures, and uncertainty for the time being …
- For simplicity, assume demand is the same in both periods
    - $MB = 8 - 0.4q$
- And the cost of taking oil out of the ground is the same in both periods
    - Marginal extraction cost = 2

The Problem of using Static Efficiency Criteria (P = MC) with Nonrenewable Resources

<u>Simple Example:</u>

- Two periods
- Constant marginal cost of extraction = 2
- Demand: $P = 8 - 0.4q$
- Static efficiency: P=MC each period → extract 15 units in each period
- OK if stock is ≥ 30 units
    - MB=MC both periods
- But what if stock is < 30?
- **Q: How should 20 units be allocated?**



How should 20 units be allocated?

- Could set Q1 = 15
  - This leaves Q2 = 5
  - Is this efficient?
  - No:
    - Marginal net benefits at Q1 = 15 are approx = 0
    - In period 2, at Q2 = 5, MB – MC = 8-.4*5 – 2 = 4
    - *Moving a unit from present to future increases welfare*

- Could set Q1 = Q2 = 10
  - Is this efficient?
  - Not if we value the present more than the future

From Static to Dynamic Efficiency

- Question: To maximize present value of net benefits, how should extraction be divided between two periods?
- "Intuitive" Response: Allocation must be such that *present value of the marginal net benefit* of last unit in each period must be the **same**.
- Rationale: Otherwise, just shift a unit of extraction from one period to other, and thereby increase total present value.
- **Formal Solution:**
  - Set present value of net marginal benefits equal in both periods

$$(MB1 - MC1) = (MB2 - MC2)/(1+r)$$

Steps for solving analytically

- First calculate **marginal net benefits** in each period:
  - MB1 – MC1 = P1 – MEC1 = 8 – .4q1 – 2 = 6 – .4q1
  - MB2 – MC2 = P2 – MEC2 = 8 – .4q2 – 2 = 6 – .4q2
- Set the **present value** of marginal net benefits equal in both periods.
  - **Efficiency Constraint (EC):** (MB1 – MC1)= (MB2 – MC2)/(1+r)
    - Here we assume r = .10
- Next, impose the **Resource Constraint (RC)**: q1 + q2 <= Q total
- This gives two equations and two unknowns
  - From RC: q2 = 20 – q1
  - Plug into EC:

$$(6 - .4q1)*1.1 = 6 - .4q2$$

$$6.6 - .44q1 = 6 - .4(20 – q1) = .4q1 – 2$$

$$q1^* = 8.6/.84 = 10.24$$

$$q2^* = 20 – 10.24 = 9.76$$

Graphical solution

Steps:

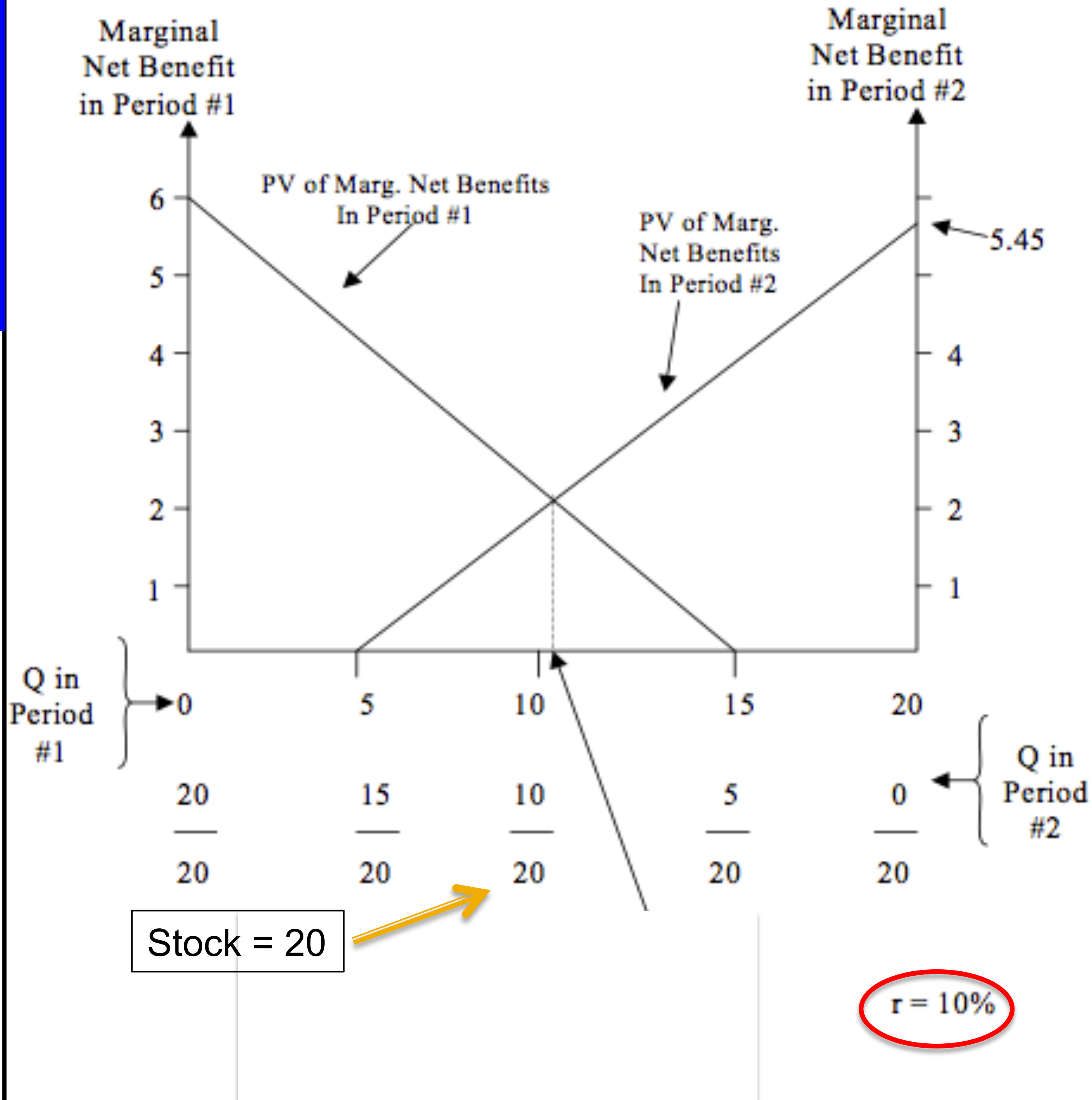
1. Place extraction each period on opposing axes, separated by resource constraint
2. Plot the **present value** of marginal net benefits in each period
   - So divide period 2 by 1+r
3. The intersection is the optimal allocation.

How can you tell this is the optimal point?

- Graphically show PV of Surplus (Net Benefits)
- What would PV of surplus be if q1=5, q2 = 15?

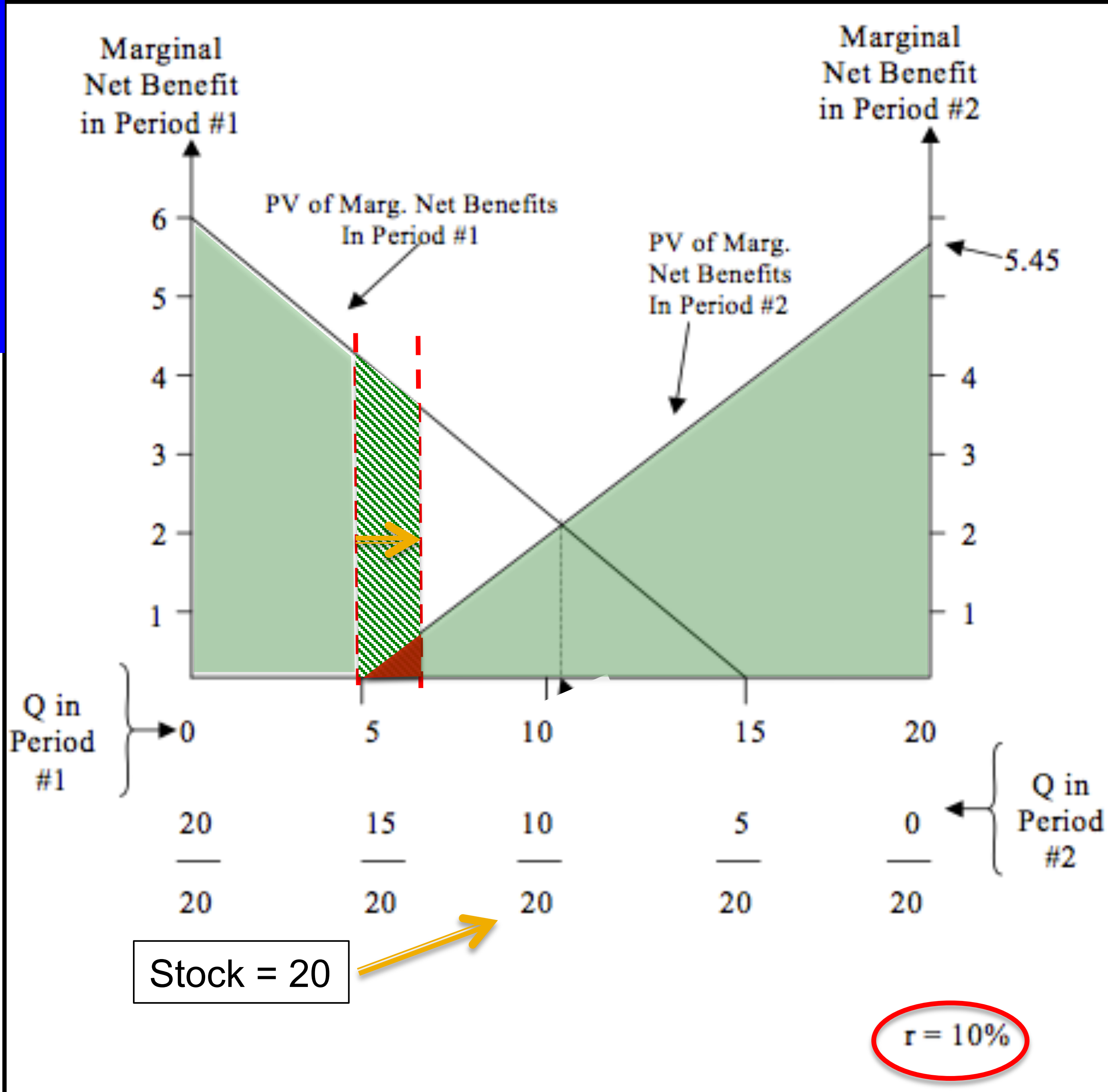
Dynamic Efficiency in a Simple Two-Period Model

- Place both periods on same graph
  - X axis spans stock
- Plot **Present Value** of **Net** marginal benefits
  - Subtract MB – MC each period
  - Convert to PV using 1/(1+r) for the future



Dynamic Efficiency in a Simple Two-Period Model

- When we maximize discounted net benefits, optimal allocation is
  - $q_1 = 10.238$
    $q_2 = 9.762$
- <u>How do we find the price in each period?</u>
- We can't look at the y-axis, that is marginal net benefits



Solving for equilibrium prices in each period

- We just solved for the efficient quantities
  - $q1^* = 10.238$
  - $q2^* = 9.762$
- We know that quantity lies on the demand curve, which is a function of price.
- So we can just plug q1 and q2 back into demand to get prices
  - $MB1 = 8 - .4 * 10.238 = 6 - .4q1 = 3.905$ ← Period 1 price
  - $MB2 = 8 - .4 * 9.762 = 6 - .4q1 = 4.095$ ← Period 2 price

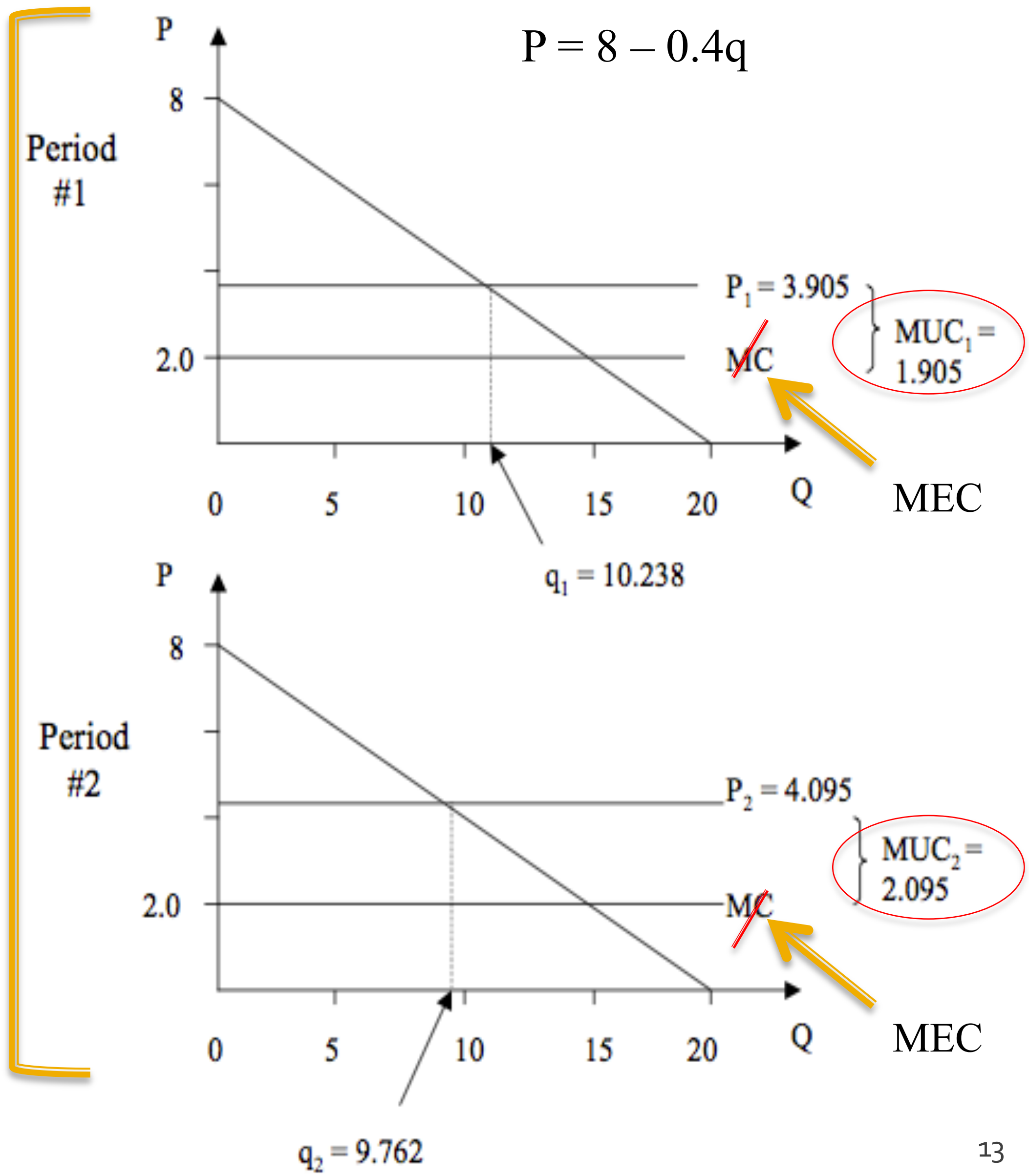
- In both periods, the efficient price is higher than the marginal cost of taking oil out of the ground (P > MC).
  - What is going on here? Why is that efficient?

The efficient price is not marginal cost! (the usual static efficiency condition). Why?

- Scarcity: greater current use means fewer future opportunities.
- Definition: **Marginal User Cost** (MUC) is the present value of these foregone future opportunities.
- So, true MC = Marginal Extraction Cost (MEC) + MUC
- Price *does* equal marginal cost:

  P = MC = MEC + MUC

- So, **MUC = P – MEC**
- Failure to take **increasing scarcity value** of resource into account will lead to inefficiency (extra future social cost to society).



Scarcity and Marginal User Cost

- Use of resources that is economically appropriate in absence of scarcity, may no longer be economically appropriate when scarcity is present.
  - Recall that if there were 30 units available in previous example, there'd be no scarcity (MUC = 0). Efficient output occurs at P = MEC.
  - But with only 20 units available, scarcity exists.
- What is this Marginal User Cost?
  - Also known as scarcity value or **scarcity rent**
  - "**Shadow price**" of the *in situ* resource
- We found: MUC = \$1.905 in Period 1 and MUC = \$2.095 in Period 2
  - It's *increasing*, but present value of MUC is *constant*!
    - MUC1 = 1.905 = MUC2/(1+r) = 2.095/(1.1)
  - MUC is just the marginal net benefits in each period, and our efficiency condition sets the present value of that equal across periods
- It turns out that is a general property of how prices for nonrenewable resources should change over time

The Hotelling Rule

- Dynamic efficiency requires that the *present value* of MUC is *constant* over time.
  - In other words, **MUC is *rising at the rate of interest*.**
  - This is the **Hotelling Rule**: It is *efficient* for "net price" (P – MEC) to rise at the rate of interest (*Journal of Political Economy 1931*):

Condition for Dynamic Efficiency ➡

$$\frac{(P-\dot{MEC})}{(P-MEC)} = r = \frac{\dot{MUC}}{MUC} \approx \frac{2.095-1.905}{1.905} = .100$$

In previous example..

where $\dot{x} = \dfrac{dx}{dt}$

- Look at this as *arbitrage condition* (why it's efficient at individual level)
  - Note that P - MEC is potential profit. Let λ = scarcity rent (shadow price of *in situ* resource), then:

Time rate of change of *potential profit* = time rate of change of *shadow price of resource in the ground* ("implicit bank") = Capital Gain

$$\frac{\dot{\lambda}}{\lambda} = r$$

Interest Rate

Comparative statics (on graph)

- **What happens if we become less patient? (ie increase the discount rate)**
  - Intercept on second Y-axis = (P-MEC)/(1+r)
  - As r goes, up, the PV of net benefits decreases
  - Efficient to **consume more today**

- **What happens if we expect innovation to decrease marginal extraction costs in the future? (ie MEC2 < MEC1)**
  - This is what happened during the fracking revolution
  - Now the whole curve in the future shifts up (MEC2 decreases)
  - Efficient to **consume more in the future** when its cheaper to extract

Will an Unregulated Market be Efficient?

- **Theory**: With a complete and perfect system of **property rights**, the market achieves dynamic efficiency.
  - Property rights means everyone agrees which entity can decide how and when a resource is used.

- Why does the market "work" in this setting?
  - Resource owners **care** about value of ***in situ* stock**, *not only* today's extraction price
  - There's a **potential capital gain** on asset in the ground
  - Owners take account of and receive the **scarcity rents**

- **Empirical**: *General agreement* with the patterns described above:
  - Many studies (one by Margaret Slade, 1982) have found this pattern for minerals and fossil fuels over 100 years (copper, iron, nickel, silver, zinc, coal, natural gas, petroleum)

- **Hotelling Valuation Principle**: *Ex ante* market value of reserves equals current scarcity rent (p – mec) times quantity of reserves. Affirmed (Livernois).

Example: Saudi Aramco

Clearly MUC > 0

- Approximate MEC: $2/bbl
- Current oil price: $85/bbl

- Do you think the Saudi extraction rate is equal to the social optimum?
  - Faster? Slower?

Conditions under which Unregulated Market may *not* be Dynamically Efficient

1. **Imperfect information** (↑↓?)
   - But may still be *efficient conditional upon available information*
2. **Non-competitive market structure** (↓)
   - Monopolies, cartels (OPEC)
3. **Poorly defined property rights** (↑) *
   - Common-property or open-access resources
   - Example: Ogallala Aquifer
4. **Negative Externalities** (↑) *
   - Related to extraction or to use (later)
5. **Difference between private and social discount rates** (↑↓?)

Summary of Key Topics

1. Nonrenewable resources are characterized by an **intertemporal externality**. Using a resource today reduces the stock available for future generations.
2. Efficient resource extraction maximizes the present value of net benefits.
3. The true marginal cost of extraction is the **opportunity cost** of the resource. This includes the marginal extraction cost and the scarcity rent (marginal user cost).
4. The Hotelling Rule describes a rule for extracting resource optimally. In the simplest case, it states that the scarcity rent should rise at the discount rate across two periods.
5. If property rights are well defined, and the market is competitive, a private resource owner will extract resources at the dynamically efficient rate.

Additional Material

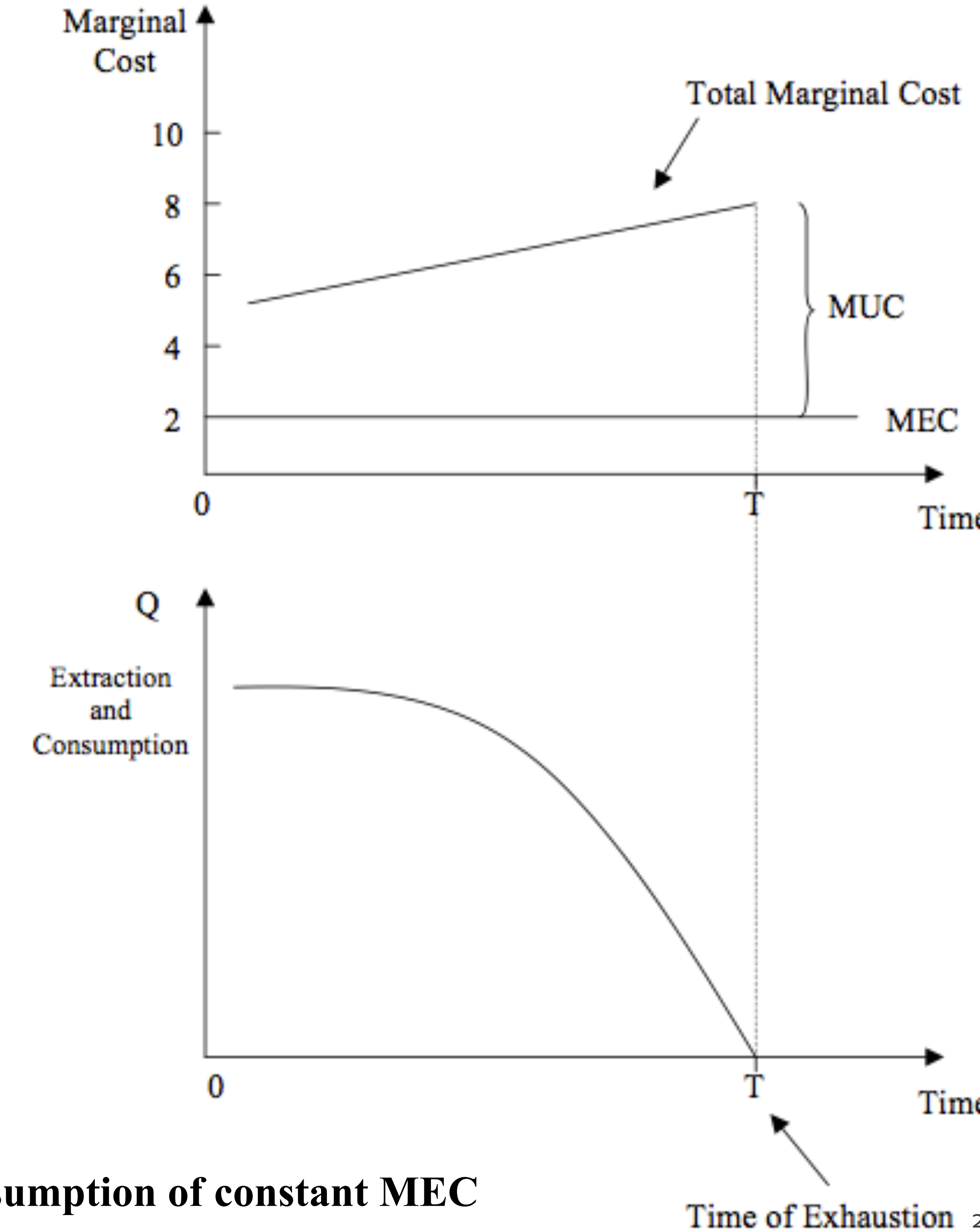
Generalizing Dynamic Efficiency to N Periods

- **Quick Review**
  - With nonrenewable resource with fixed & finite supply, production of a unit today *precludes* production of a unit in future.
  - So, efficient for production decision to take **foregone future net benefits** into account; **MUC** is *opportunity cost measure* that allows this balancing to take place.
- **Hotelling Rule**: In efficient allocation over time, *current value* of MUC rises over time (present value *constant*)
  - *MUC rises at rate of interest* (with stable demand, constant marginal extraction cost, no discovery, no market failures, etc. --- later), preserving appropriate balance between present and future production
  - Production falls over time, as total marginal costs rise.
- In simple two-period model, results **derived** graphically, but results of N-period model will only be **presented**, because I can't draw n-dimensional graph!
  - Can be derived rigorously, however, using "calculus of variations" or "optimal control theory" (see *optional* handout at course web site if interested)

Dynamic Efficiency in a Simple N-Period Model

Model generalizes to n periods:

- MUC increases over time
- Total marginal cost increases, reaches reservation price of demand (with constant marginal extraction costs)
- Exhaustion occurs
  - Not a surprise, given our demand function
  - What if asymptotic? Then, not efficient to exhaust.
- **More important: let's relax assumption of constant MEC**



Dynamic Efficiency with Increasing Marginal Extraction Cost

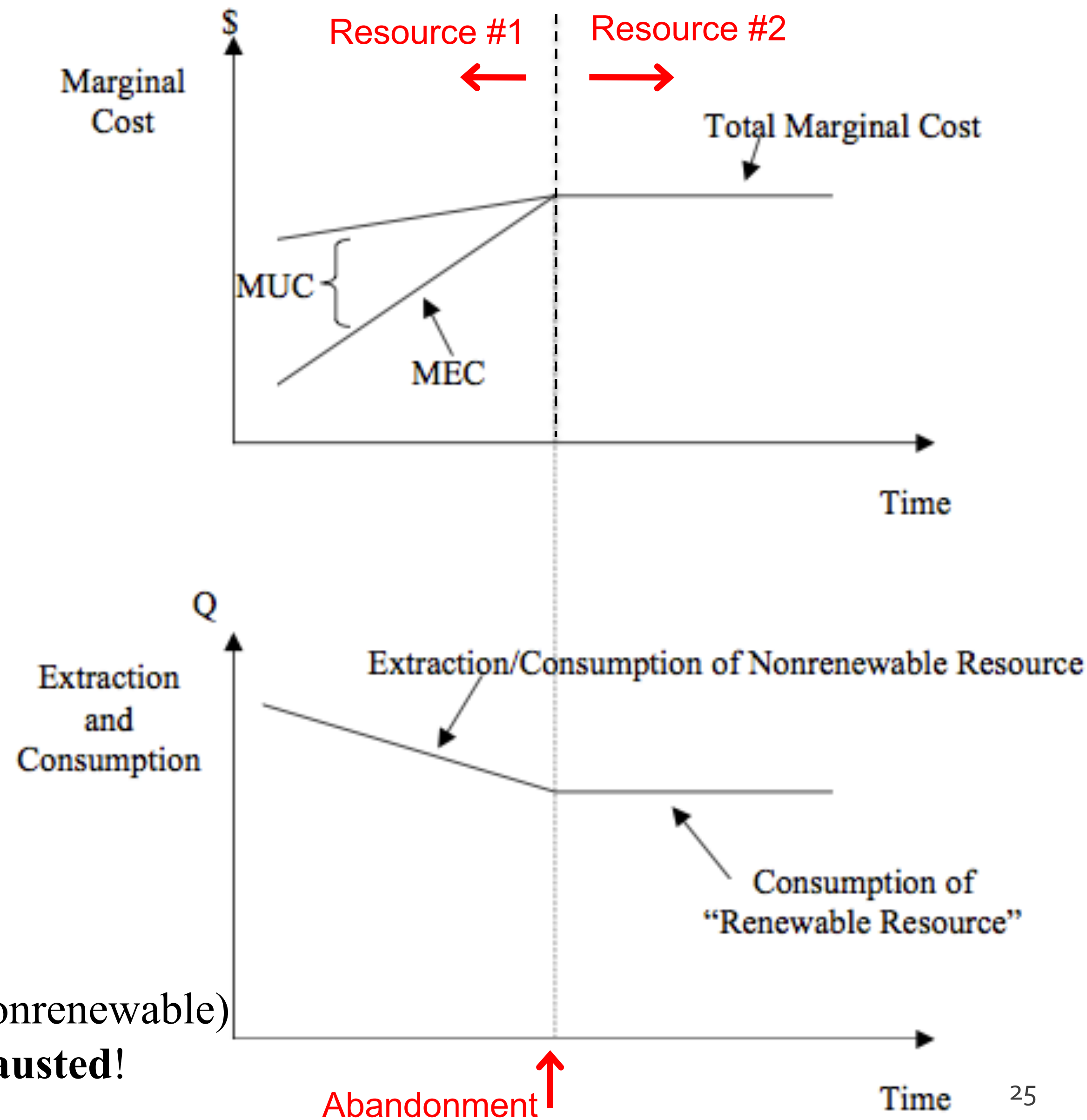
- Real World: MECs increase as a function of *cumulative extraction*. Why?
  - Extract ores closer to surface first (examples: coal, petroleum, etc.)
  - Extract higher grade ores first (primary, secondary, tertiary recovery of minerals)
- So, as *stock* decreases, MEC increases:

$$\text{MEC} = f(\underset{(-)}{\text{Stock}}, \underset{(+)}{\text{Extraction Rate}})$$

- Recall: *Marginal User C*ost is a measure of foregone *future net benefits*.
  - With MEC increasing over time, marginal net benefits decrease over time.
  - So, *MUC decreases over time*.
- Intuition: As we deplete, who *cares* if we've only got a bit left
  - if the MECs are approaching choke price of demand (small net benefits)
  - … or are approaching, equal to, or greater than marginal cost of some substitute (backstop technology). [Think about depleting peat, knowing that there's coal.]
  - So, MUC → 0 (under specific conditions)

Increasing Marginal Extraction Cost with Substitute Resource

- **Scarcity** is an economic, not simply a physical reality.
- As MECs get larger and larger, *in situ* value **decreases**, and we're hurting future generations less and less, on the margin.
- Eventually, **opportunity cost** of current extraction drops to zero, and total marginal cost simply equals MEC at **transition point**.
- Whereas, **exhaustion** is typically efficient with constant MECs,
- With increasing MECs, **abandonment of the stock** is typically **efficient**.
- Lots of examples: Exhaustible (nonrenewable) resources are virtually **never exhausted**!

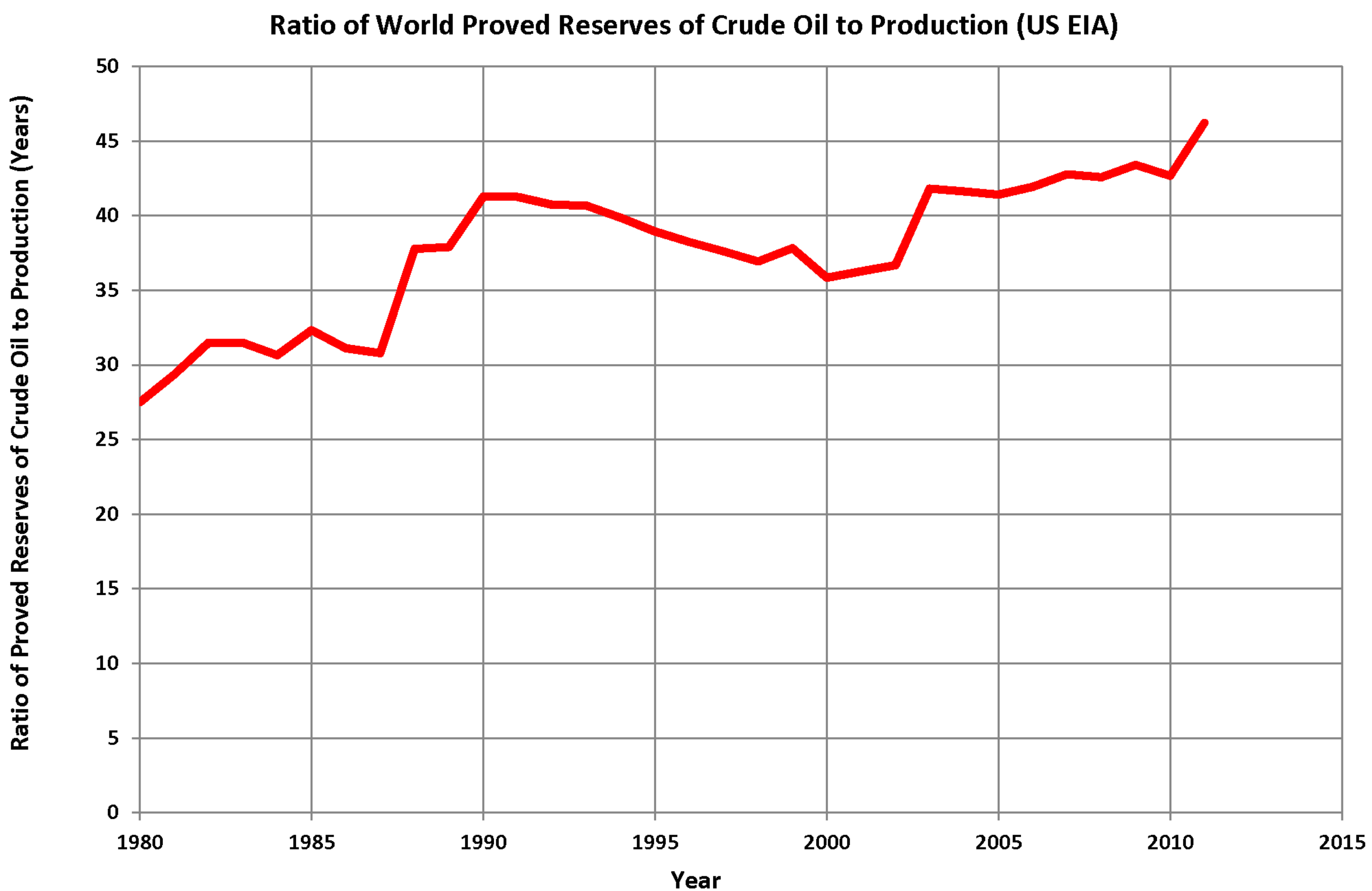


Nonrenewable Resources: Rate of Use

- **Reserve-to-Use Ratio** frequently cited by press & government studies:

$$\frac{Current\ reserves}{Annual\ use} = \frac{45,000,000\ tons}{1,000,000\ tons\ /\ year} = 45\ years$$

Despite increasing use and production each year, global RTUR increasing



Nonrenewable Resources: Rate of Use

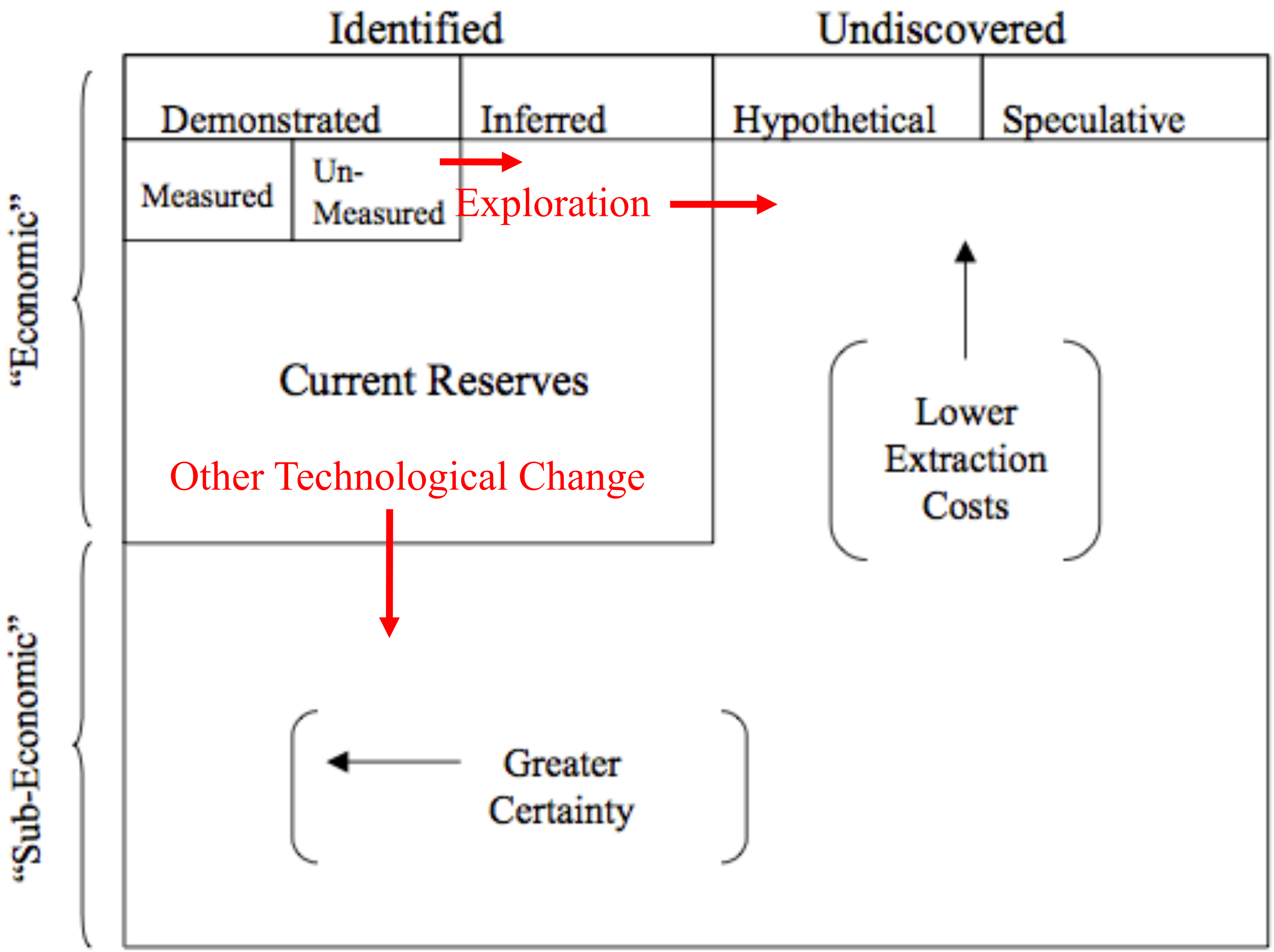
- **Reserve-to-Use Ratio** frequently cited by press & government studies:

$$\frac{Current\ reserves}{Annual\ use} = \frac{45{,}000{,}000\ tons}{1{,}000{,}000\ tons\,/\,year} = 45\ years$$

- What does *static reserve-to-use ratio* (*RTUR*) mean? Virtually nothing!
- What's wrong with RTUR as indicator of scarcity, time left of a resource?
    1. Ignores declining rate of use as price increases
    2. Ignores newly discovered reserves
    3. Ignores newly economic reserves as price increases

- A graphic view of what's going on …

McKelvey Diagram of Resource Stocks



Exploration and Technological Progress

- Let's **relax two more assumptions**: first, allow for **exploration and discovery**
  - Discovery of new stocks *can* (does not necessarily) result in *declining MEC* over time.
  - So, total marginal costs can *decrease* over time
  - Hence, consumption may increase for some period of time.
- Second, **technological progress** can yield downward shift of MEC function
  - So, total MC can decrease over time (even as lower-grade ores are extracted)
- In other words, discovery & technological change can **overcome** "stock effect" (at least, for some period of time).
- But eventually, *decreasing returns* to exploration and tech R&D set in. Then, stock effect dominates, and total MCs rise.
- Rather than a monotonically downward-sloping extraction path over time and an upward sloping MEC time path, dynamic efficiency would be a **U-shaped pattern** of MEC and price and **a reverse-u-shaped pattern of extraction**.