Natural Resource Economics: Nonrenewable Resources

Dynamic Efficiency, Markets, & Market Failure

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Nonrenewable Resource Economics

I. Categories of Natural Resources

II. Dynamic Efficiency in a Simple Two-Period Model *(limits of static view)*

III. Scarcity and Marginal User Cost

IV. Generalizing the Model by Relaxing Assumptions

   A. N Periods

   B. Case of Increasing Marginal Extraction Costs

   C. Exploration and Technological Progress

V. How Does the Market Perform?

VI. Summary

Taxonomies of Natural Resources

- **Exhaustible (vs. Inexhaustible) Resources**

  (Hotelling 1931; Dasgupta & Heal 1979)

  - Exhaustible
    - Finite quantity, i.e., rate of generation trivial compared with rate of use
    - Examples: fossil fuels (coal, petroleum, & natural gas), and minerals
  - Inexhaustible
    - High rate of generation or regeneration (relative to use/decay)
    - Examples: water (exception – Ogallala Aquifer) & living species, forests

- This taxonomy is problematic …

Taxonomies of Natural Resources

- **"Exhaustible vs. Inexhaustible Resource" Distinction is Problematic – Why?**
  - So-called "exhaustible resources" are *difficult or impossible* to exhaust, because …
    - Cheaper to extract – deposits that are *closer to surface* or *higher-grade* ores – are extracted first
    - So, costs of extraction increase over time, i.e. *supply function* shifts up and to the left
      - Market *price increases*; prices choke off demand …
      - Quantity extracted *decreases* …
    - At some price, *substitutes* become attractive. Examples …
      - *Pea*t extracted as energy source in Britain nearly 2000 years ago; still there
      - Stanley Jevons' 1865 prediction: *coal* will be exhausted in less than 100 years
      - Nearly universal substitution in transportation sector from coal to *petroleum*
      - Etc, etc.

Taxonomies of Natural Resources

- **More about Problematic Nature of "Exhaustible vs. Inexhaustible Resource" Distinction**
  - "Inexhaustible resources" – the biological ones – can indeed be totally *depleted (exhausted).* Why?
    - Stocks do *not* have to be reduced to *zero* for extinction to occur.
    - One example …
      - Passenger Pigeons – 3 to 5 billion in the USA when Europeans arrived in North America. Extinct by early 20th century. Why?
      - Hunting (harvesting) – economic issue (*open-access* resources – later)
      - Habitat Loss – consequence of economic activity
      - Natural rate of decline overwhelms growth rate (critical depensation)
      - Hunters did not need to shoot the last mating pair for extinction to occur

Bottom Line: "Exhaustible resources" are ***not*** exhausted; "inexhaustible resources" sometimes ***are*** exhausted!

Taxonomies of Natural Resources

- **An Alternative (and Better) Taxonomy**
  - **Nonrenewable natural resources**
    - Growth (regeneration) rate is essentially zero
    - Examples: Fossil fuels and minerals
  - **Renewable natural resources**
    - Positive growth (regeneration) rate
    - Examples: living species
  - Renewables are typically *more threatened* by market activity (i.e., departures from efficient harvest/extraction)

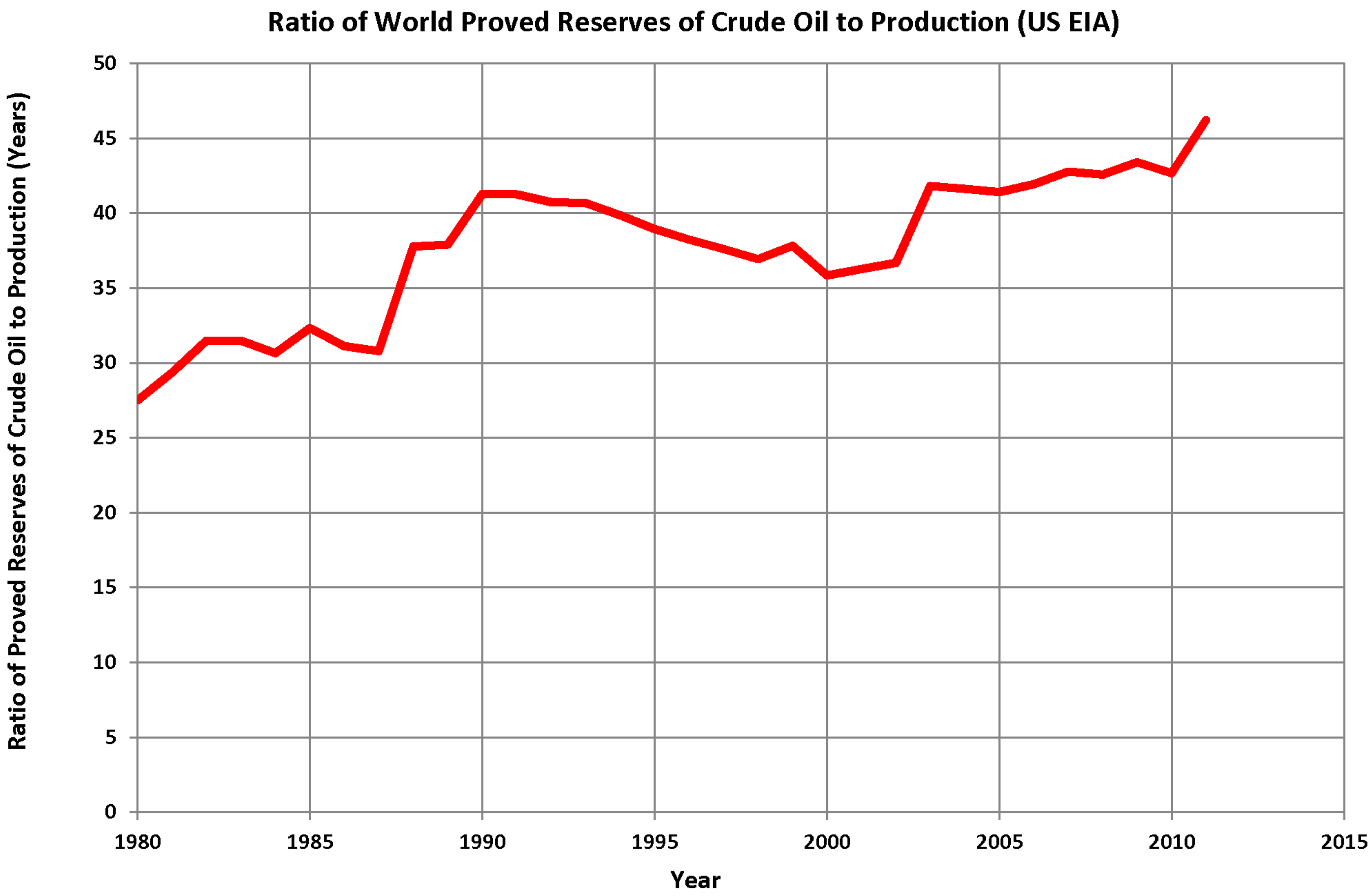
- We focus on nonrenewable resources *first.* Why?
  - Simpler analytically than renewables
  - Nonrenewable is special case of renewable resource with zero growth

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

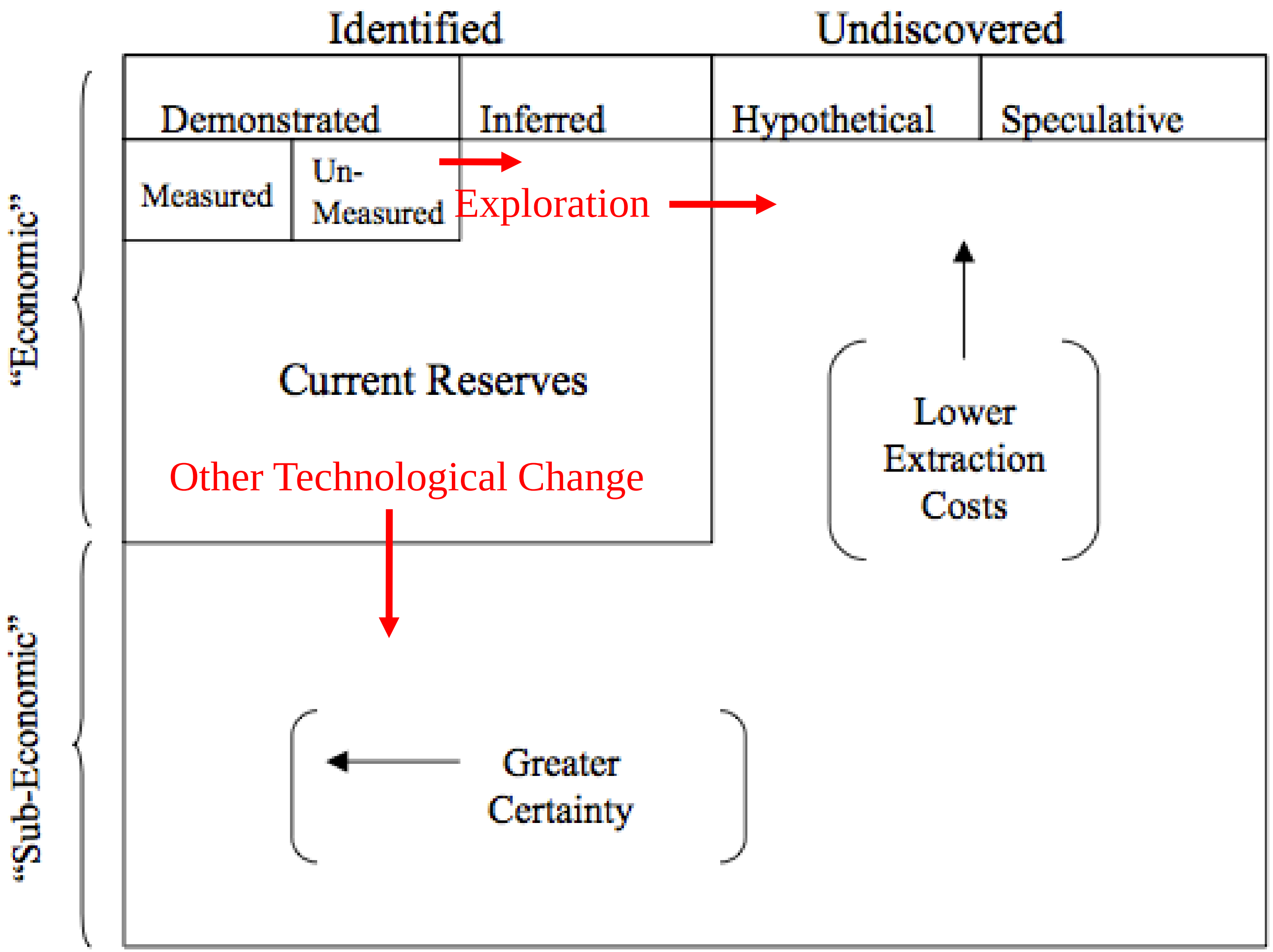
- **Reserve-to-Use Ratio** frequently cited by press & government studies:

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

- 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



Dynamic Efficiency

Question: How fast should nonrenewable resource stock be extracted?

- Economic response: *efficient* rate of extraction

What does efficiency mean in this context?

- MB = MC
- Where MC includes **opportunity cost**
- Here there is a unique dynamic opportunity cost: If you use a

Nonrenewable resources involve a specific opportunity cost

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

Dynamic Efficiency

Question: How fast should nonrenewable resource stock be extracted?

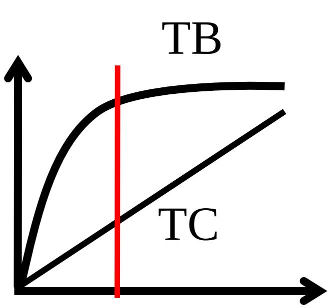
- So, real economic response is the "*dynamically efficient rate*"
  - Maximizing present discounted value of future net benefits
- Let's look at this a bit more rigorously in a ...
  - Simple Two-Period Model
  - Put aside environmental externalities, other market failures, and uncertainty for the time being …

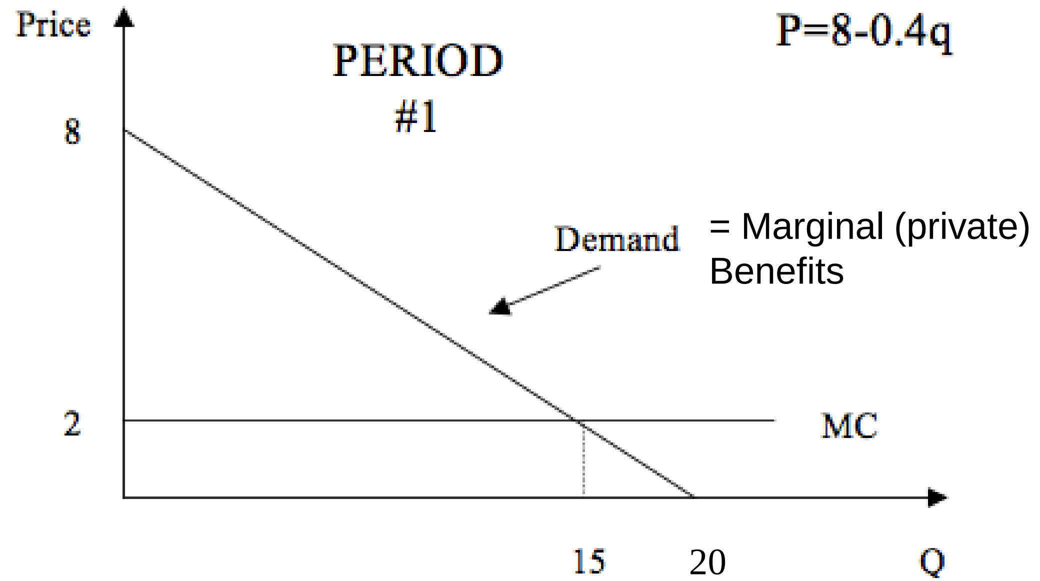
The Problem of using Static Efficiency Criteria with Nonrenewable Resources

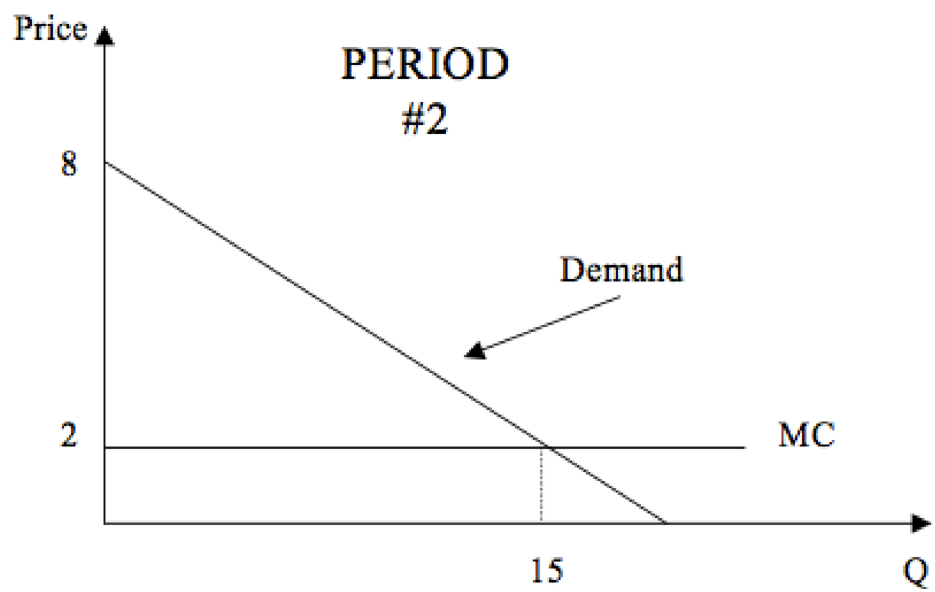
Simple Example:

- 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?**

Reminder:







How should 20 units be allocated?

- Could set Q1 = 15
  - This leaves Q2 = 5
  - Is this efficient?
  - No:
    - MB1 = 8-.4*15 = 2
    - MB2 = 8-.4*5 = 6

- Could set Q1 = Q2 = 10
  - Is this efficient?
  - Not if we value the present more than the future
  - Want to discount *marginal net benefits*

From Static to Dynamic Efficiency

- General 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**.
  - Why?
  - 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

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

- We can derive this and more with graphical version of dynamic optimization model …

Analytical solution

- First calculate marginal net benefits in each period:
  - MB1 – MC1 = P1 – MEC1 = 8 - .4q1 – 2
  - MB2 – MC2 = P2 – MEC2 = 8 - .4q2 - 2
- Set **present value** of net marginal benefits equal in both periods

  Efficiency Equation: (MB1 – MC1)= (MB2 – MC2)/(1+r)
  - Assume r = .10
- To solve, take advantage of Resource Constraint: q1 + q2 <= 20
- This gives two equations and two unknowns
  - From RC: q2 = 20 – q1
  - Plug into EE:

    (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

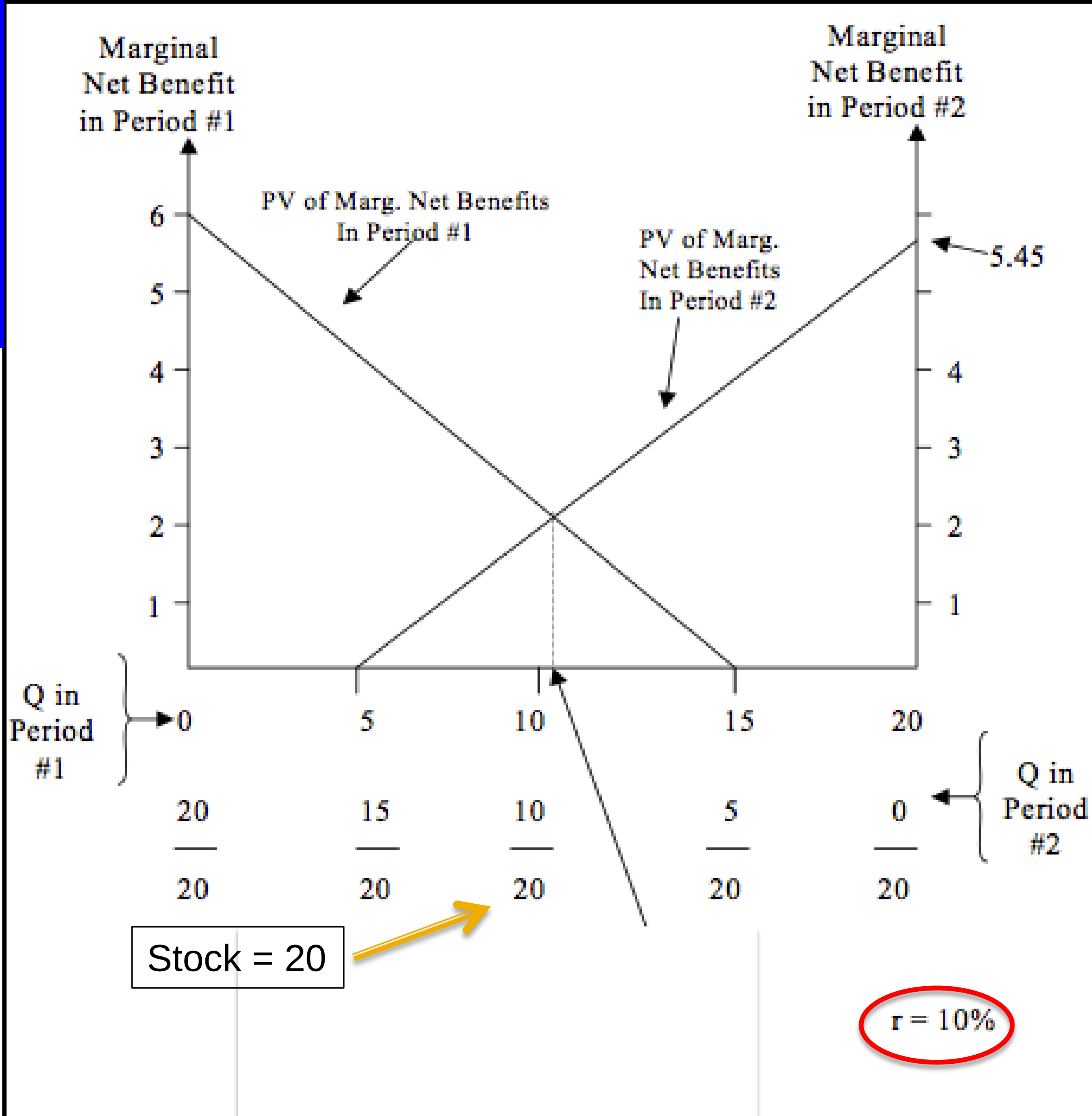
- Can also see optimal point graphically

Steps:

- Place on opposing axes, separated by resource constraint
- Plot PV MNB in each period
- Intersection is the optimal allocation.
- How can you tell this is the optimal point?
    - Graphically show PV of Total Benefits
    - What would the total benefits be if q1=5, q2 = 15?

Dynamic Efficiency in a Simple Two-Period Model

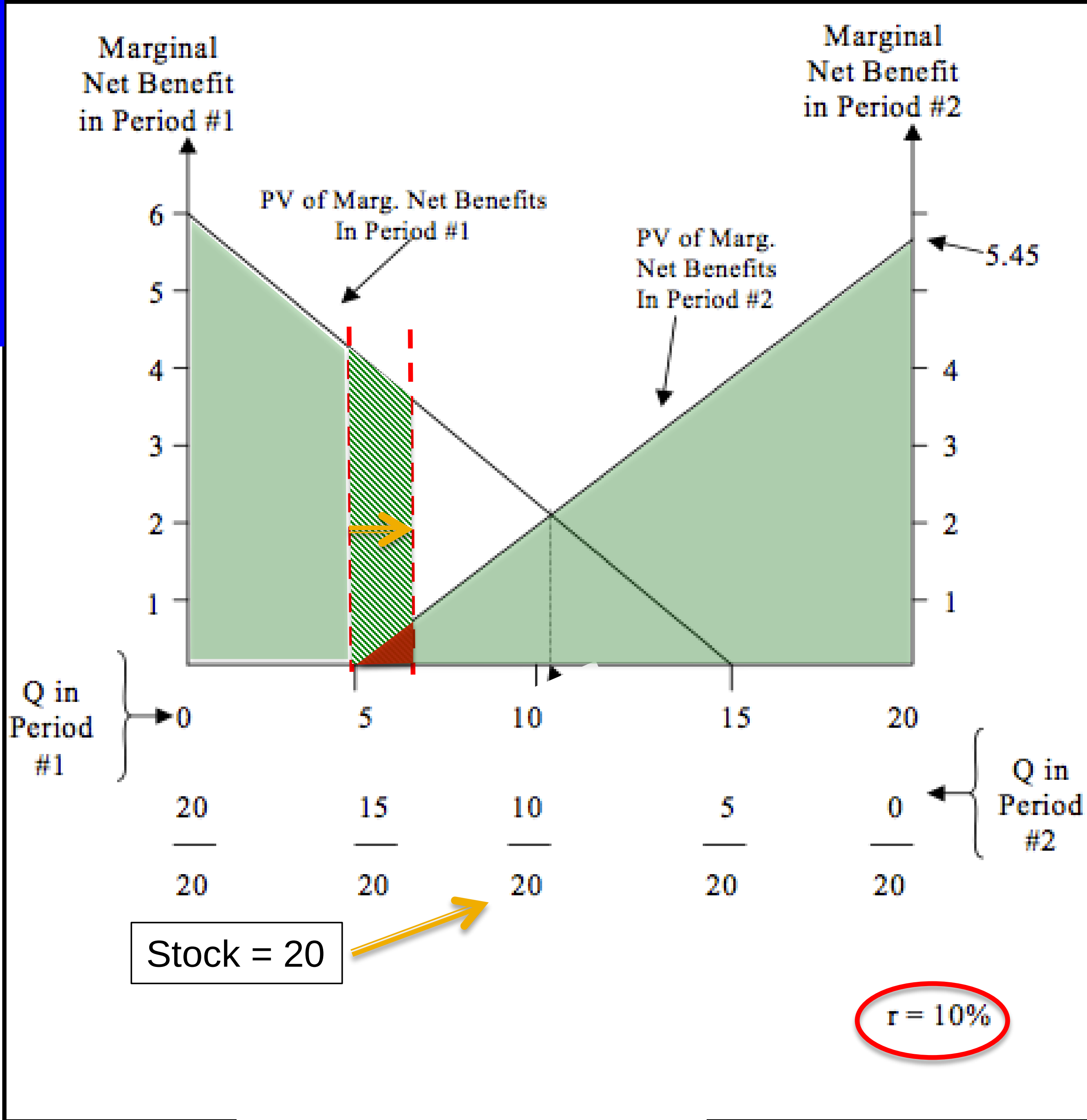
- Place both periods on same graph
  - X axis spans stock
- Plot **Present Value** of **Net** marginal benefits
  - Subtract MB – MC each period
  - Convert to PV using 1/(1+r) for the future



Dynamic Efficiency in a Simple Two-Period Model

- When we maximize total net benefits, optimal allocation is
  q_1 = 10.238
  q_2 = 9.762
- By substituting quantities into the demand function,
  p_1 = 3.905
  p_2 = 4.095
- The actual (real – without inflation) *prices in the two periods are different.*

  …what's going on?



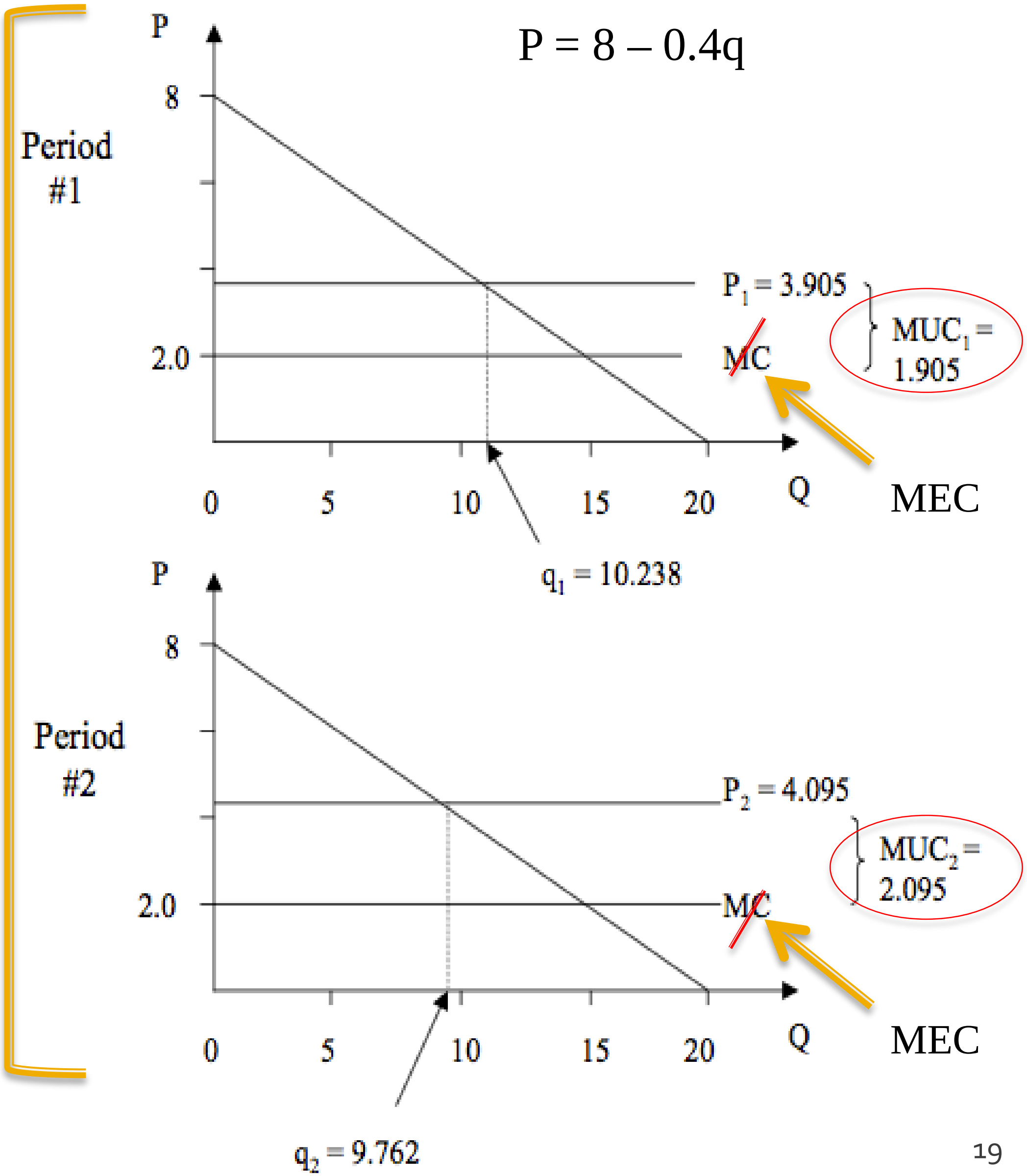
Dynamic Efficiency with Constant Marginal Costs

- So, we have dynamic efficiency
- But in neither period is P equal to MC (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).
  - 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
  - Analytically, it's the **Lagrange Multiplier** in a constrained optimization
  - Analytically, it's the **costate variable** in dynamic optimization (optimal control)
- 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*! (link w/previous intuition)
  - Clearly, both MUC & efficient extraction rate are affected by the discount rate
  - But how?

The Hotelling Rule

- So, for dynamic efficiency, *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 $\dot{x} = \frac{dx}{dt}$

- 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 increase the discount rate?**
  - Intercept on second Y-axis = (P-MEC)/(1+r)
  - As r goes, up, the PV of net benefits decreases
  - So we consume more today
- **What happens if we decrease MEC in the future (say through innovation)?**
  - Now the whole curve in the future shifts up (MEC2 decreases)
  - Consume more in the future when its cheaper to extract

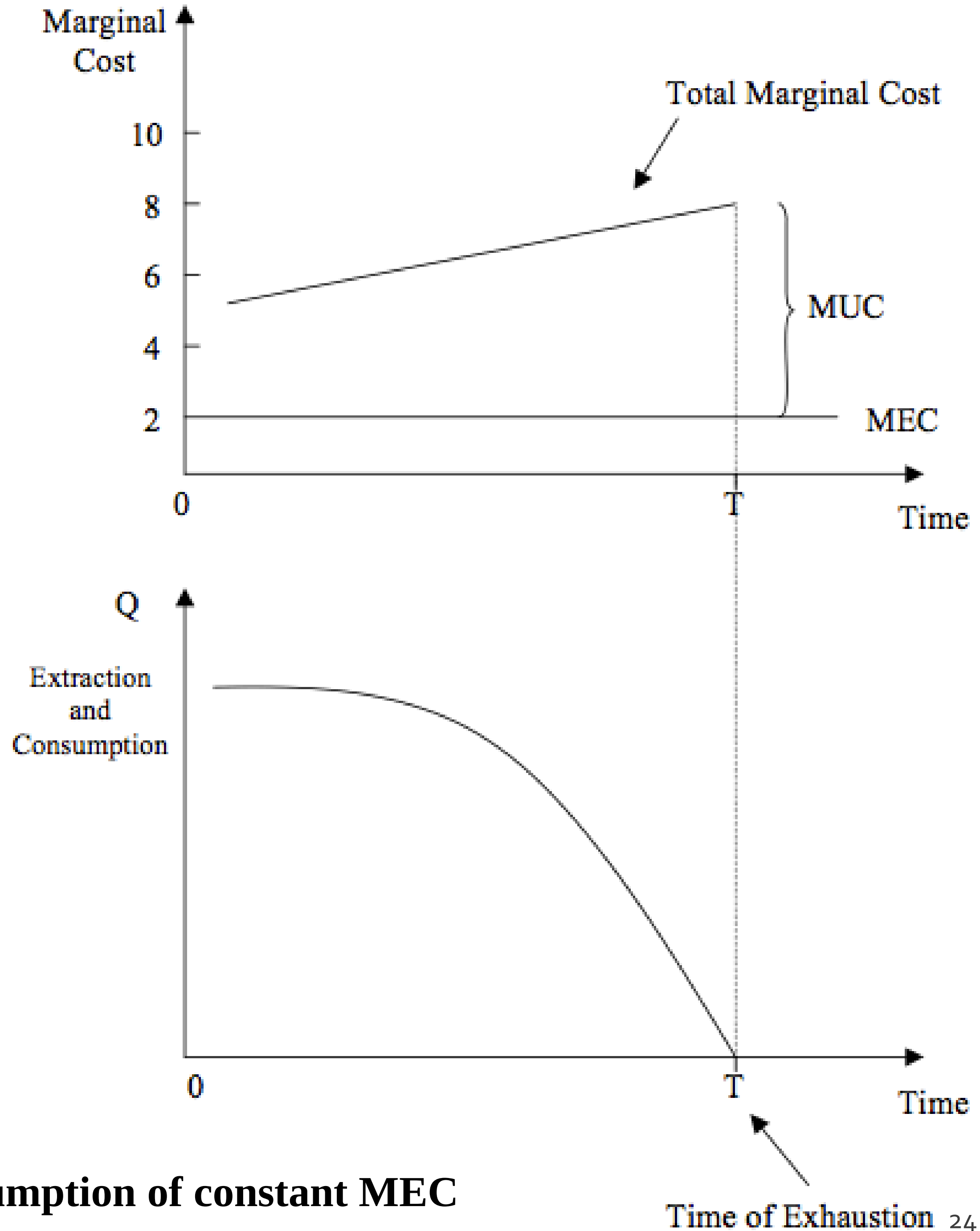
Generalizing Dynamic Efficiency to N Periods

- **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

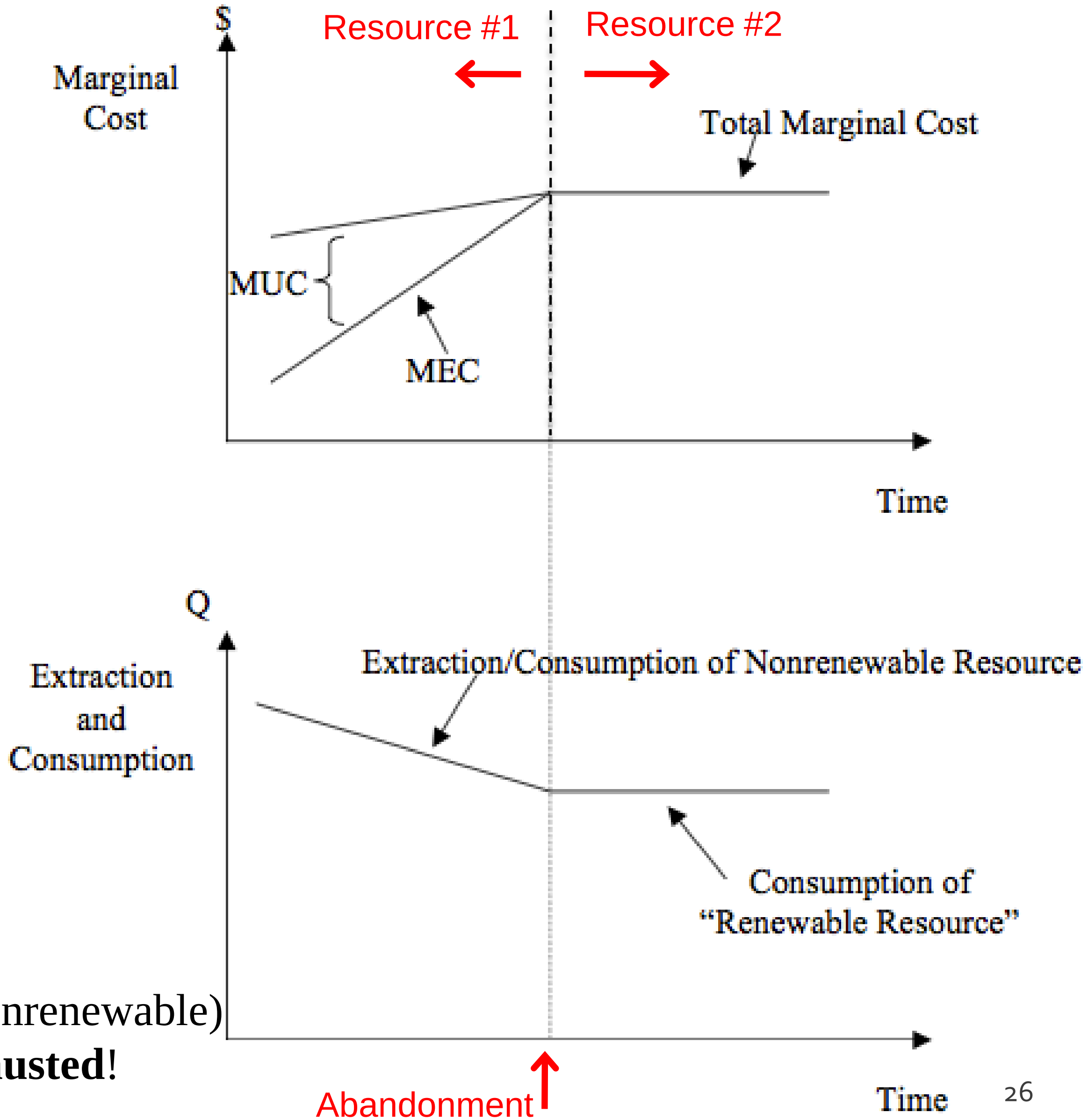
- Real World: MECs increase as a function of *cumulative extraction*. Why?
  - Extract ores closer to surface first (examples: coal, petroleum, etc.)
  - Extract higher grade ores first (primary, secondary, tertiary recovery of minerals)
- So, as *stock* decreases, MEC increases:

MEC = f(Stock, 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)

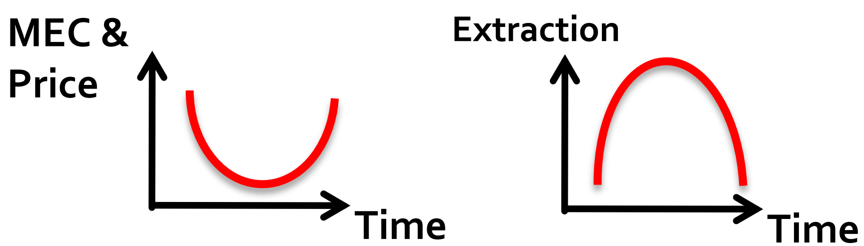
Increasing Marginal Extraction Cost with Substitute Resource

- **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**!



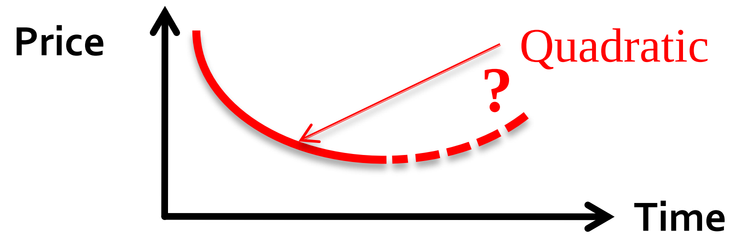
Exploration and Technological Progress

- 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**.



Will an Unregulated Market be Efficient?

- **Theory**: With a complete and perfect system of property rights (as defined earlier), market achieves dynamic efficiency in each of previous cases. Why?
  - 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)



- **Important Exception**: Some **renewable resources** have exhibited *monotonically increasing price, increasing extraction costs, increasing scarcity.* (Next class)
- **Hotelling Valuation Principle**: *Ex ante* market value of reserves equals current scarcity rent (p – mec) times quantity of reserves. Affirmed (Livernois).
- For *nonrenewable resources*, when is the market **not** dynamically efficient?

Critical role of property rights

- If an individual or firm owns the resource, and has the same discount rate, his profit maximizing extraction path matches the social optimum (caveats on next slide)
- If no one owns the stock, it becomes a race to extract
  - Why save the resource for someone else?
- Example: Ogallala Aquifer
  - Large water source underlying 174,000 miles in U.S. Great Plains
    - Repleneshment rate ~ 1/10th extraction rate
  - Water is **open-access**: anyone who pays extraction costs can take it
  - As a result, it is being depleted as a rate much faster than the social optimimum

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)

- **Deviations** from "perfect vacuum" result in resource extraction **above or below** efficient rate
- **Rebuttable Presumption** is that markets for **nonrenewable** natural resources tend to be "close" to dynamically efficient.
- When we examine many **renewable** resources, we'll find that **opposite** rebuttable presumption is reasonable.

5. **Difference between private and social discount rates** (↑↓?)

Summary of Key Topics

1. Taxonomies of natural resources
2. Reserve-to-use ratio & McKelvey diagram of resource stocks
3. Problem of static efficiency criterion in case of nonrenewable natural resources
4. Dynamic efficiency criterion
5. Graphical derivation of dynamically efficient time path of extraction in simple two-period model with constant MEC
6. Economic scarcity, marginal user cost, scarcity rent, shadow value of in-situ resource
7. Hotelling Rule
8. Generalizing dynamic efficiency to N periods with constant MEC
9. Prevalence of increasing MECs
10. Dynamic efficiency with increasing MECs
11. Effects of exploration/discovery and technological progress
12. Theory and empirics of relative efficiency of unregulated nonrenewable resource markets
13. Conditions under which market extraction rates depart from dynamically efficient rate