Real Options and Environmental Economics: An Overview

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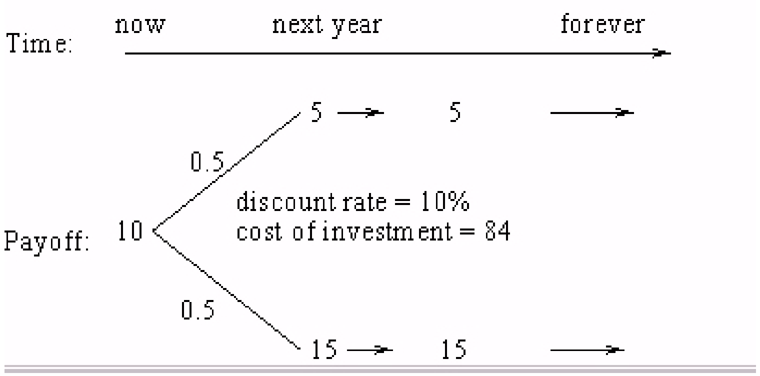
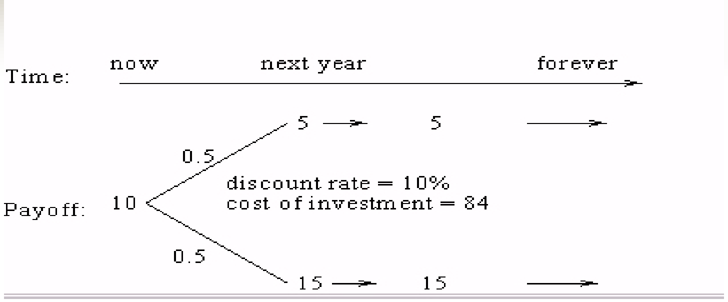
I. Real Options In A Nutshell

- Example: risk neutral planner



- Expected NPV = 10/0.1-84=$16
  - Go ahead: invest *now*

Example cont'd



- BUT: what if waiting till next year to decide?
  - If unfavorable (\$5), 5/.1 < 84:
    - Don't invest!
  - If favorable (\$15), 15/.1-84= \$66
    - Invest
  - Expected payoff = (.5)(66)/1.1=\$30
- Should *not* invest now! (30 > 16)
- Delay helps avoid unfavorable investment that you will regret given the new information

What is the story?

- Hysteresis: waiting has value when
  - There is uncertainty in payoff of investment
  - You can learn in the future by delaying
  - You can delay the investment
  - Investment is irreversible or costly reversible
- The value is called *option value*
  - Much like financial option value
    - Example: call option: opportunity to invest in year two
    - Value is $30
  - Investment now kills this option
  - Invest now only if ENPV ¸ OV, or if the benefit can cover both the cost and the OV
- Investment now competes not only with no-investment, but also with investment later

II. A Brief History

- Weisbrod (1964)’s conjecture
  - Park has value even if I don’t visit it
  - Reason: possible visits, in the future
- Two interpretations of Weisbrod
  - Option price, due to risk attitude
    - Zeckhauser (69), Cicchetti and Freeman (71), Ready (’95)
    - Risk premium (or option value): difference between WTP and expected CS, or *ex ante* and expected *ex post* welfare measures
    - No dynamic decision
    - But, can be negative, depending on the concavity/convexity of marginal utility functions
  - (Quasi-) option value: due to arrival of new information
    - Maintain the flexibility of responding to new information
    - Independent of risk attitude
    - Dynamic framework with learning
    - Always positive
    - Conditional value of information

The OV literature

- Started with Arrow and Fisher (1974), Henry (1974)
- Branching Out:
  - Information service, Bayesian updating
    - Epstein ('80), Freixas and Laffont ('84), Jones and Ostroy ('84), Demers ('91)
    - Role of information, ranking of informativeness (Blackwell's measure)
    - Mostly discrete time, two or three periods
  - The Dixit-Pindyck framework
    - Much like financial modeling, similar to Black and Scholes
    - Information follows a stochastic process
    - New info: new observed value of the variable
- Applications
  - Res., env., and ag., economics
  - General econ: labor, investment, exchange rate, real estate
  - Industrial engineering: capital budgeting, to account for managerial flexibility

III. The Dixit-Pindyck Framework

- Basic Idea: McDonald and Siegel (1986)
  - An investment project whose value V_t follows geometric Brownian motion:

$$dV_t = \alpha V_t dt + \sigma V_t dz_t$$

  - dz_t is increment of Weiner process
    - dz_t » N(0, dt): "scale" of dz_t is pdt
    - dz_t and dz_s are independent, for $t \neq s$
    - Typical of stock prices
  - Decision problem:
    - When to incur cost of I to lock in the project
    - Or at what value of V_t to invest
    - If V_0=V, and discount rate is ρ (maybe risk adjusted), then ($\alpha < \rho$)

$$F(V) = \max_T E e^{-\rho T} [V_T - I]$$

Two Solution Methods:

- Contingent claims analysis
  - Similar to valuation of financial options: another version of Black and Scholes
  - Applicable when the risk dz_t can be spanned by existing assets in financial markets: *rich* set of assets
  - Market has to be in equilibrium: no arbitrage
  - Can value F without any assumption about the discount rate or the investor's risk attitude (without knowing ρ):
    - The price of the *option* is *relative to* other assets that are traded in the market
- Dynamic programming, or optimal stopping
  - Has to assume a discount rate
  - Applicable to many environmental problems

III.1 Solution method: DP

- Bellman equation for F(V)

$$F(V(t)) = \max\{V(t) - I, e^{-\rho dt} E[F(V(t+dt))]\}$$

Not straightforward to solve: discrete decision

- Trick: transform into optimal stopping
  - Exists a critical value V^* so that
    - Continuation region: wait if $V<V^*$

$$F(V(t)) = e^{-\rho dt} E[F(V(t+dt))]$$

    - Stopping region: invest if V ¸ V^*

$$\Omega(V(t)) = V(t) - I$$

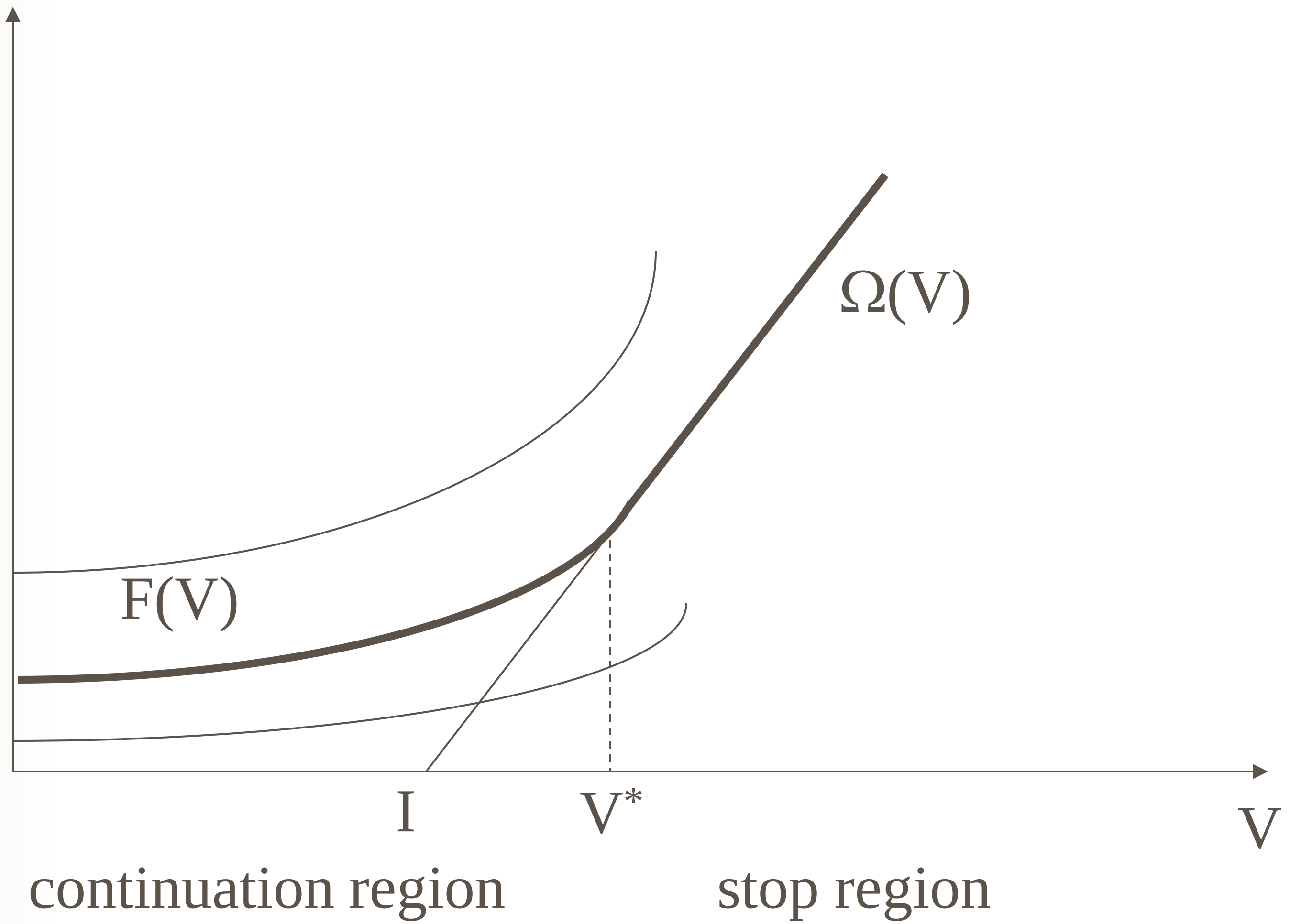
    - At V^* (due to max{¢, ¢})

$$\text{Value matching}: F(V^*) = \Omega(V^*)$$
$$\text{Smooth Pasting}: F_V(V^*) = \Omega_V(V^*)$$

Optimal stopping

- Conditions for connected regions, divided by V^*
  - Monotonicity conditions for both payoffs and distribution of V(t+dt) given V(t)
  - Satisfied by most problems
  - Intuition: if V is high, the opportunity cost of waiting, V-I, is high
- Value matching and smooth pasting conditions
  - VMC: intuitive, true if both F(¢) and Ω(¢) are continuous
  - SPC: trickier, true if both functions are continuously differentiable (Dixit 1993)

Optimal stopping, with VMC and SPC



The continuation region

$$F(V(t)) = e^{-\rho dt} E[F(V(t+dt))]$$

Rewrite the equation

$$F(V(t)) = (1 - \rho dt)(F(V(t)) + EdF(V(t)))$$

Letting dt ! 0

$$\rho F(V) = \frac{E(dF(V))}{dt}$$

Expected return = ρ

Apply Ito's Lemma $dV_t = \alpha V_t dt + \sigma V_t dz_t$

$$\begin{aligned} dF(V) &= F'(V)dV + \frac{1}{2}F''(V)(dV)^2 \\ &= F'(\alpha V dt + \sigma V dz) \\ &\quad + \frac{1}{2}F''(\sigma^2 V^2 dt + o(dt)) \end{aligned}$$

Ordinary differential equation

$$\frac{1}{2}\sigma^2 V^2 F''(V) + \alpha V F'(V) - \rho F(V) = 0$$

Boundary conditions are provided by VMC and SPC, as well as the natural economic condition (free boundary!)

$$F(0) = 0$$
$$F(V^*) = V^* - I$$
$$F'(V^*) = 1$$

Guess a solution to the PDF: $F(V) = AV^{\beta}$

Fundamental quadratic:

$$\frac{1}{2}\sigma^2\beta(\beta - 1) + \alpha\beta - \rho = 0$$

Roots: $\beta_1 > 1$, decreasing in σ;

$\beta_2 < 0$, increasing in σ

Solution

General solution:

$$F(V) = A_1 V^{\beta 1} + A_2 V^{\beta 2}$$

Impose the boundary conditions

$$F(0) = 0$$
$$F(V^*) = V^* - I$$
$$F'(V^*) = 1$$

$$F(V) = A_1 V^{\beta_1}$$
$$V^* = \frac{\beta_1}{\beta_1 - 1} I$$
$$A_1 = \text{some constant}$$

Interpretation of the results

$$V^* = \frac{\beta_1}{\beta_1 - 1} I$$

- Hysteresis: $V^* > I$
  - More reluctant to invest, compared with neoclassical investment rule ($V^* = I$)
    - Don't want to jump as V may rise further
    - VMC $V^* = I + F(V^*)$: return from investment has to overcome both cost I and option value F
  - Investment barrier increases
    - As uncertainty rises: V^* increasing in σ^2
    - As ρ decreases: cost of waiting goes down
- Investment barrier vs. probability of investment
    - Move in same direction if exogenous changes do not affect the distribution of V_t
    - As σ^2 rises, investment prob may rise or fall (Sarkar, 2000)

III.2 Solution method: contingent claims

Optimal stopping by definition:

- Holding an option F(V), and when to exercise it?

Suppose there exist spanning assets, replicating the risk dz

$$dx = \mu x dt + \sigma x dz$$

Market equilibrium:

- CAPM: μ is determined by the market

$$\mu = r + \phi \rho_{xm} \sigma$$

- Exercising the option
  - Assume $\mu > \alpha$, otherwise, will never exercise the option
  - Convenience yield, or dividend rate: δ ´ $\mu - \alpha$

Forming a riskless portfolio

- Long one option: F(V)
- Short n=F'(V) units of x, or the investment project
- Value of the portfolio: $\Phi = F - F'(V)\,V$
- Return from the portfolio over dt
  - Change in value (capital appreciation): dF – ndV
  - Dividend payout: δ V n dt
  - Total return: $dF - F'(V)dV - \delta\, V\, F'(V)\, dt$
  - Applying Ito's Lemma to dF
    $dF = F'(V)dV + .5\, F''(V)\, \sigma^2\, V^2\, dt$
  - Deterministic total return:
    $(1/2)\sigma^2 V^2 F''\, dt - \delta\, V\, F'\, dt$
- Equilibrium: return = r
  $(1/2)\sigma^2 V^2 F''\, dt - \delta\, V\, F'\, dt = r\, \Phi\, dt = r(F-F'V)dt$
- Similar ODE:

$$\frac{1}{2}\sigma^2 V^2 F''(V) + (r-\delta)VF'(V) - rF(V) = 0$$

Compare with DP

- The same boundary conditions: VMC and SPC
- Compare the ODEs

$$\frac{1}{2}\sigma^2 V^2 F''(V) + \alpha V F'(V) - \rho F(V) = 0; \quad \text{(DP)}$$

$$\frac{1}{2}\sigma^2 V^2 F''(V) + (r-\delta) V F'(V) - r F(V) = 0; \quad \text{(Mkt equil)}$$

Risk neutral valuation:

Replace ρ by r

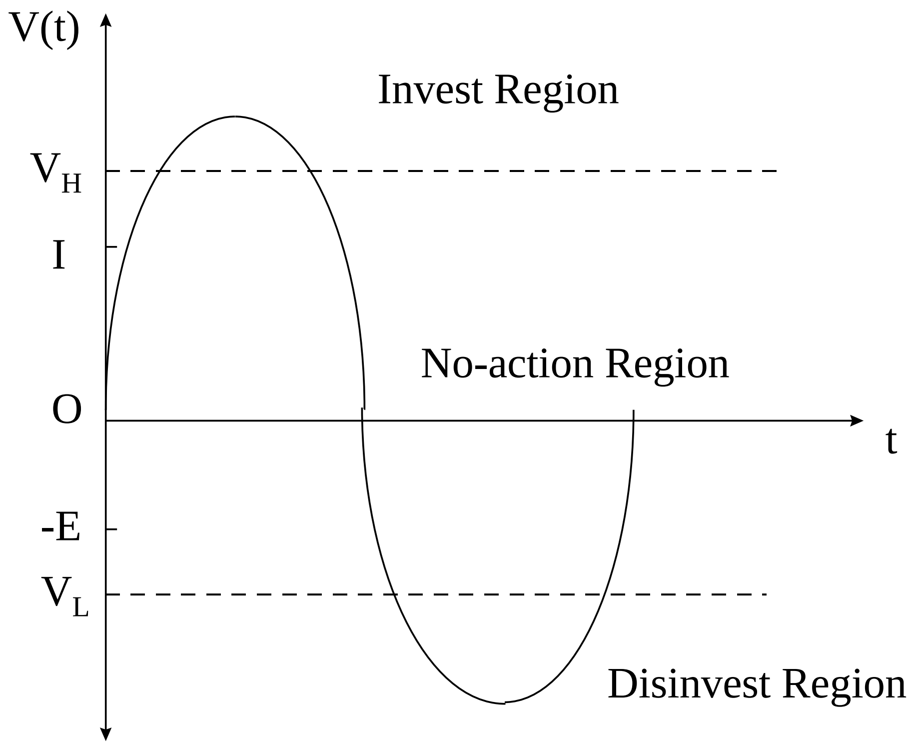
Replace expected return α by (r-δ),

valued under the risk neutral probability

III.3 Extensions of the basic model

- Endogenous process of dV
  - Production with variable output, temporary suspension, price uncertainty
  - Solution: find process for V first
  - Essentially the same results
- Different stochastic processes
  - Mean-reversion
  - Poisson jump
  - Reflecting barriers
- Entry and exit (invest and disinvest)
  - Sunk fixed fees for entry and exit
  - Reluctant to do either
    - Entry: future price may go down (regret!)
    - Exit: future price may go up (regret!)
    - Area of inaction

Entry and exit: two barriers



III.3 Extensions (cont'd)

- Continuous investment levels
  - Choose how much to invest, rather than whether invest or not
  - Trick: decide the marginal unit, or the last unit
    - If willing to invest this unit, all earlier units should be invested
    - Similar results
- Multiple stages
  - A project may require many stages to complete
  - Each stage incurs sunk cost
  - Most reluctant to start earlier stages:
    - More info at later stages
    - Higher loss if regret

Extensions

- Competitive equilibrium
  - No monopoly in investment opportunity
  - If wait, other firms may invest, driving down the price
  - Surprise: the *same* investment rule (Leahy, 1993; Baldursson and Karatzas, ’97; Zhao, forthcoming)
  - Intuition:
    - Entry of other firms: price ceiling
    - Investment today competes with investment tomorrow
    - Price ceiling reduces both values, without changing their *relative* value

Recent Extensions

- Double sided irreversibility
  - Kolstad, JPubE, 1996
  - Both abatement investment and global warming damages are irreversible
  - Investment depends on the relative prob and costs of the two irreversibilities
- Multiple options
  - Some research in capital budgeting, Trigeorgis, 1993
  - Depends on whether the multiple stages are complements and substitutes (Weninger and Zhao, 2002)
    - Willing to invest early if complements: creates more future flexibility
    - Less willing to invest if substitutes, in order to preserve future flexibility

Recent extensions

- Strategic interactions
  - Not much research: Dutta and Rustichini, ET, 93
  - The strategic relationship may increase or decrease the value of remaining flexible, depending on the form of interaction
- Endogenous learning
  - Miller and Lad, 1984
  - Experimentation literature (Mirman et al, 92, 93,..)
- Empirical research
  - Econometrics
    - Very few: Paddock, et al. QJE, 1988; Quigg, 1993;
  - Simulation: growing (Slade, 2001)
  - Structural estimation (Rust's methodology)?

IV. Applications in Env. & Res. Econ.

- General applications
  - **Resource extraction, development and management** (Brennan and Schwartz, ’85a,b; Stenslandand Tjostheim,’85; Paddock, Siegel and Smith, ’88; Trigeorgis,’90; Lund, ’92; Rubio, 1992; Zhao and Zilberman, ’99; Mason,’01; Weninger and Just, 2002)
  - **Species preservation** (Krutilla, 64; Fisher, Krutilla and Cicchetti, ’72; Fisher and Hanemann, 1986)
  - **Global warming** (Nordhaus, ’91; Ulph and Ulph, ’97; Kolstad, ’96a,b)
  - **Abatement investment under different policies** (Xepapadeas,’99; Chao and Wilson,’93; Zhao, forthcoming)

Applications

- Policy making, endogenous irreversibility
  - Pindyck, 2000: a new policy may be hard to reverse
    - Gradual changes in policy, rather than one big decision
  - Zhao and Kling, 2002:
    - Initial policy change may set a trend that is hard to reverse
    - Then even more cautious
      - Similar to facing a fixed cost
      - Very reluctant to change initially, but once decides to change the policy, the change is relatively big

Environmental policy

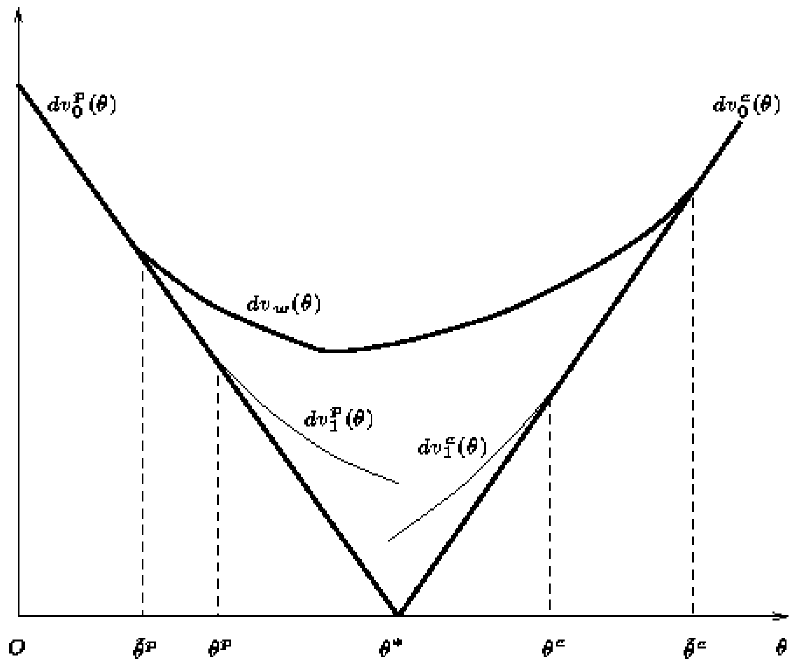


Figure 3: Optimal Policies Before and After the Policy Trend is Set

Application: env. valuation, WTP/WTA

- Key result in applied welfare analysis:
  - CV = WTP and EV=WTA (for price decrease, quality increase)
  - WTP ¼ WTA, except for income effects (and later on, Hanemann’s substitution effects)
  - Behavior based measurements vs. value measurement
- A typical CVM study:
  - How much are you willing to pay to preserve a park
  - WTA to get rid of it
  - WTP/WTA values are taken as measures of CV/EV

However,

- If the subject
  - Is uncertain about the value of the park or substitutes/complements
  - Expects that she can learn about the value
  - Has some willingness to wait
  - Expects a cost of reversing the action of buying or selling (the only survey!)
- Then, she may choose to wait for more info before making a decision
- But, in surveys/experiments, she has to form a WTP or WTA offer *now*, with existing info
  - She needs compensation for the lost option value
  - Lower WTP: WTP < CV/EV
  - Higher WTA: WTA > CV/EV
  - The wedge is the *commitment costs* (Zhao and Kling, '01, '02)

Predictions

- WTP increases
  - As the subject is more familiar with the good
  - If she cannot delay: only chance to vote on the referendum
  - If she can't learn much in the future
  - If she can easily reverse her vote (hard to do?)
- Predictions also form hypothetical tests

Empirical tests/evidence

- CVM study: Corrigan, Kling and Zhao (2002)
  - Clear lake study in Iowa
  - One group offered the opportunity of vote again one year later
  - Different levels of uncertainty (hard to manipulate)
  - Commitment cost can be 25% - 57% of static WTP (i.e. without learning)
  - WTP decreases in the option of delay
  - Responses to uncertainty somewhat weak
- Market experiments: Kling, List and Zhao (2002)
  - Sports card trading
  - Ask subjects' perceptions about delay and reversal costs
  - Confirms predictions
- Lab experiments: Corrigan (2002)
  - Weak evidence in trading of cookies
  - Better design and more experiments are needed

Implications

- Neither WTP nor WTA may measure CV/EV accurately, if CCs are high
- Some CCs are part of the decision, but some should be removed (esp if you want to measure the expected consumer surplus, or the *value*)
- Design surveys carefully to
  - Get rid of CC or OV (or estimate the magnitude)
    - More information
    - Delay vs. no delay (Hellat's Quarry in Ames)
  - Include CC/OV to replicate the decision environment

Useful readings

- If don't want to read the book
  - Pindyck, JEL, 1991: concise math
  - Dixit, JEP, 1992: intuition, esp. for smooth pasting
- If really want to build up the theory
  - Stokey and Lucas, 1989
  - Duffie, 1992
- If want to know the field: survey books
  - Dixit and Pindyck, 1994
  - Trigeorgis, 1996
  - Schwartz and Trigeorgis, ed., 2001
- If want more opinions from me: will put reading list online

  www.econ.iastate.edu/faculty/zhao