Breakthroughs, Deadlines, and the Nature of Progress: Contracting for Multistage Projects

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Motivating example

Consider an entrepreneur (Anne) with an idea for a new product.

- Profiting from the idea requires completing two stages, e.g.,
  1. Develop a prototype
  2. Devise a cost-effective manufacturing process
- Each stage takes time, but the amount of time (and funding) needed is uncertain. Anne has no wealth.

A VC firm wants to fund the project, but faces several agency considerations:

- Anne can divert funds for private benefit, delaying progress
- Anne can (potentially) lie about the prototype

Question: How should the VC structure the contract?

- How does it depend on Anne's ability to falsify/hide progress?

More generally

- Many projects require successful completion of multiple stages before their benefits can be realized
  - Product development
  - Government procurement
  - Basic research
- Incentives of entreprenuer/employee/scientist need not be aligned with funder/firm/institution
  - Moral hazard: Agent can shirk/divert resources
  - Private information: About progress made

This Paper: explore optimal contracting for multistage projects.

- What is the role (if any) of "progress"?

What is progress?

Limited value in isolation; but a necessary step or "piece of the puzzle"

- **Tangible**: easily observable, difficult to manipulate
  - License, permit or patent
  - FDA approval
  - Number of users

- **Intangible**: privately observed by the agent, easy to manipulate
  - An idea or approach
  - An algorithm or subroutine of a larger program
  - Independently conducted experimental results

Research questions

1. How does the "nature of the progress" affect the terms of financing?
   - If progress is tangible how is it used?
   - If intangible, is there a role for communication? Is it possible to elicit progress reports and use them in a meaningful way?

2. What are the implications for how to design projects?

Findings

1. How does the "nature of the progress" affect the optimal contract?
   - If progress is tangible, how is it used?
     - When you make progress, it extends your clock. i.e., you get another round of funding.
   - If intangible, is it possible to elicit progress reports and use them in a meaningful way?
     - Yes, but not by giving additional time/funding for reported progress
     - Doing so optimally involves using a "soft deadline"
2. In designing projects and reporting requirements
   - There are benefits to
     - Imposing a "small" reporting cost (e.g., time, effort, paperwork)
     - Making the first stage somewhat "harder"
     - Eliciting information rather than obscuring it

Related theoretical literature

Dynamic agency

- Green, 1987; Spear and Srivastava, 1987; Phelan and Townsend, 1991; Quadrini, 2004; Clementi and Hopenhayn, 2006; DeMarzo and Sannikov, 2006; DeMarzo and Fishman, 2007; Sannikov, 2008...

With (observable) Poisson arrivals

- Hopenhayn and Nicolini, 1997; Biais et al., 2010; Hoffmann and Pfeil, 2010; Piskorski and Tchistyi, 2011; Mason and Välimäki, 2011; DeMarzo, Livdan, and Tchistyi (2014)

Persistent private information

- Fernandes and Phelan (2000), Battaglini (2005), Zhang (2009), Williams (2011), Edmans et al. (2012), Hu (2014), and Guo and Hörner (2015)

(Simultaneous) Multi-tasking

- Holmstrom and Milgrom, 1991; Laux, 2001; Varas, 2015

Empirical "support"

Application 1: Tangible progress in venture capital contracts, which often include

- Multiple rounds or "staged" funding
- Contingencies on non-financial performance (i.e., "progress"): Release of second major version, FDA approval, completion of clinical tests, etc.
- Right for VC to stop funding and terminate project
- Separation of cash flow and control rights

See P. A. Gompers and Joshua Lerner, 1999; P. Gompers and Josh Lerner, 2001; Kaplan and Strömberg, 2003

These features arise endogenously as part of the optimal contract for a multistage project with tangible progress.

Anectdotal evidence

Application 2: Intangible progress in funding scientific research

- According to the NSF Grant Policy Manual:

  NSF reserves the right...to withhold future funding after a specified date if the recipient fails to comply with the conditions of an NSF grant, including the reporting requirements.

- Similarly, the NIH website states that:

  If your [progress] report is extremely late, you risk losing funding...

Above features are consistent with our optimal contract with intangible progress:

1. (Costly) self-reporting requirements
2. Indefinite penalties for lack of reported progress

What this project is not about (at least thus far)

We do **not** study learning or experimentation, e.g.,

- Levitt (1997), Inderst and Mueller (2010), Manso (2011), Bonatti and Hörner (2011,2014), Hörner and Samuelson (2014), Moroni (2015), Halac, Kartik, and Liu (n.d.)

In our model, information about progress made (or lack thereof) has **no value** to a social planner

- Focus on using progress/reports to control agency costs

Model

A principal (P) contracts with an agent (A) to complete a project.

- Project requires: funding from P, expertise from A
  - P incurs flow cost to fund project prior to termination
- Completion of two stages or "breakthroughs" required to realize project benefits
- Arrival rate of breakthroughs depends on the A's hidden action
  - A can "shirk" (or divert investment) for private benefit

Model details

- Both players risk neutral, A has limited liability (trivial otherwise)
- Continuous time, no discounting (for simplicity)
- P has full commitment power

Notation

- Benefit to P if project succeeds in ultimate stage: Π
- Flow cost of operation: c
- Agent action: $a_t \in \{0, 1\}$
  - Arrival rate of breakthrough: λa_t
  - Private flow benefit from diverting resources: ϕ
- Arrival time of breakthroughs: τ_1, τ_2

First best

Assumption

The project has positive expected value

$$\Pi - \frac{2c}{\lambda} > 0,$$

and shirking (or diversion) is inefficient

$$\phi \leq c.$$

Therefore, the first-best policy involves no shirking and no termination

The contract

P offers A a contract $\mathcal{C} = \{W, T\}$

- $dW_t \geq 0$: payment to agent at time t
  - Optimal backload all payments to agent (Ray, 2002)
- T: termination policy (or stopping rule)
  - Upon termination, players get their outside options (set to zero)

Example

A **simple contract** consists of a single deadline, $T \in \mathbb{R}_+$, and a reward that depends only on the time of success.

The nature of progress

We focus on the following two extreme cases:

Definition

- *Progress is* **tangible** *if* τ_1 *is publicly observable and verifiable (hence, can be directly contracted upon)*
- *Progress is* **intangible** *if* τ_1 *is privately observed by* A *and is not verifiable*

Throughout, the ultimate success of the project (i.e., τ_2) is tangible.

- Observability not crucial, verifiability is.

Outline

1. One-stage benchmark
2. Two-stage projects
   - Tangible progress
   - Intangible progress
3. Comparison: tangible vs intangible
4. Extensions and implications for project design
5. Conclude

One-stage benchmark

Suppose that only one breakthrough is needed to realize Π

- Denote the reward for success at t by R_t
- U_t is the agent's continuation value at t

Preliminaries

1. It is optimal for the agent not to shirk/divert iff

$$\lambda(R_t - U_t) \geq \phi \tag{IC}$$

2. It is WLOG to focus on $\mathcal{C}$ with no shirking

One-stage problem

Via standard recursive methods (Spear and Srivastava, 1987)

- State variable is A's continuation value: u

The principal's value function solves the HJB equation

$$\lambda V(u) = \max_R \lambda(\Pi - R) - c + V'(u)\frac{du}{dt}$$

subject to $V(0) = 0$ and

$$\lambda(R - u) \geq \phi \tag{IC}$$

$$\frac{du}{dt} = -\lambda(R - u) \tag{PK}$$

Solution to the one-stage problem

Result

In a one-stage project, (IC) always binds. Therefore,

$$\frac{du}{dt} = -\phi \quad \text{and} \quad R(u) = u + \frac{\phi}{\lambda}$$

and the principal's value function is given by

$$V_{\text{one stage}}(u) = \left(\Pi - \frac{c}{\lambda}\right)\left(1 - e^{-\lambda u/\phi}\right) - u$$

One-stage implementation

Result

The P-optimal contract for a one-stage project can be implemented with a simple contract, where the deadline is

$$T^* = \frac{1}{\lambda} \ln \left(\frac{\lambda \Pi - c}{\phi} \right)$$

and the reward schedule decreases linearly over time

$$R_t = \frac{\phi}{\lambda} + \phi(T^* - t).$$

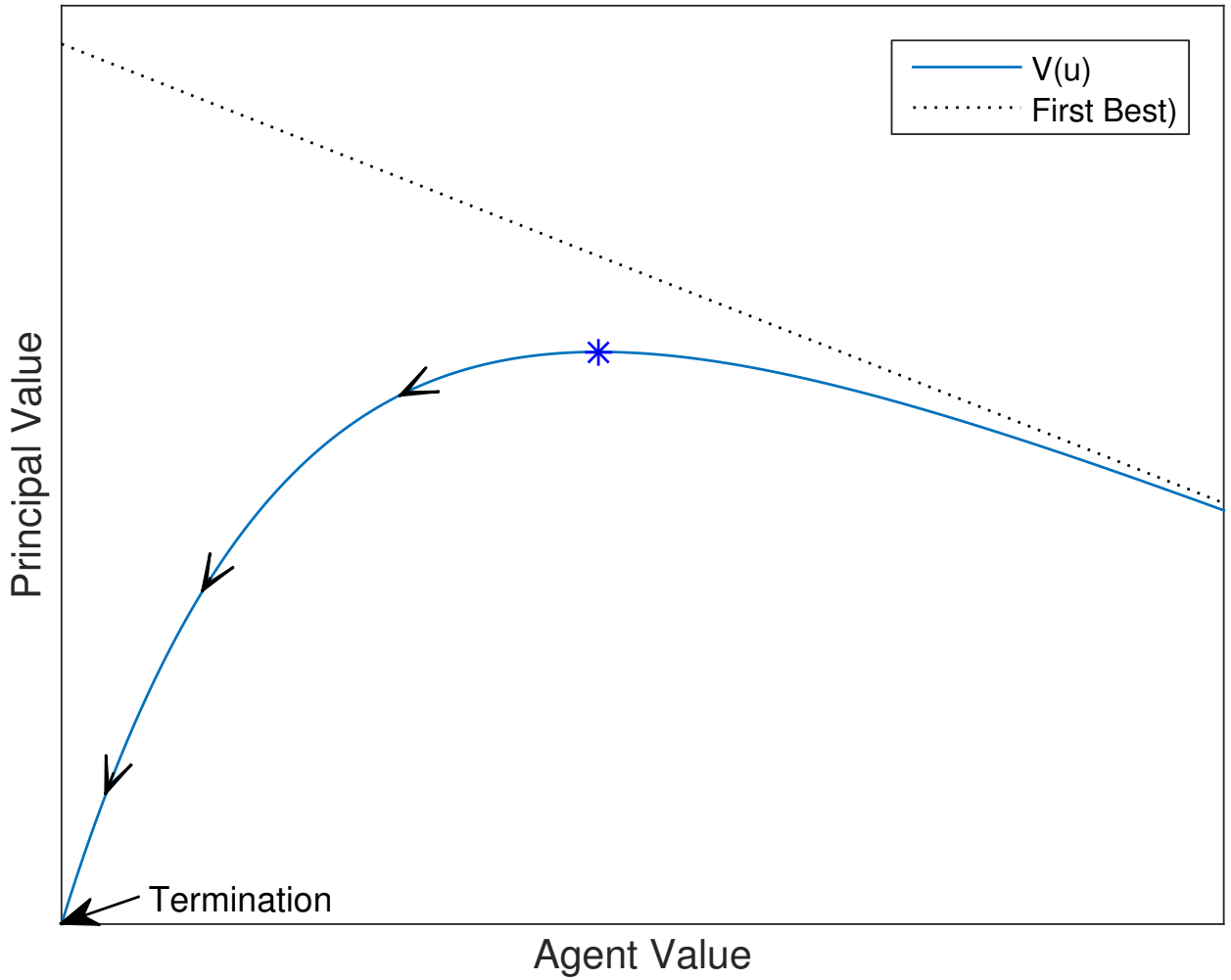
Why give a deadline?

- Stronger incentives than just using monetary payments
- Deadline is decreasing in the severity of agency conflict

$$\lim_{\phi \to 0} T^* = \infty$$

.

One-stage payoff frontier



Agent continuation value decreases over time as deadline approaches.

Two stage project with tangible progress

Benefit (Π) realized only after the second breakthrough

- First breakthrough is also tangible
- First breakthough $\implies$ increase in expected value of tangible assets, but no direct cash flow

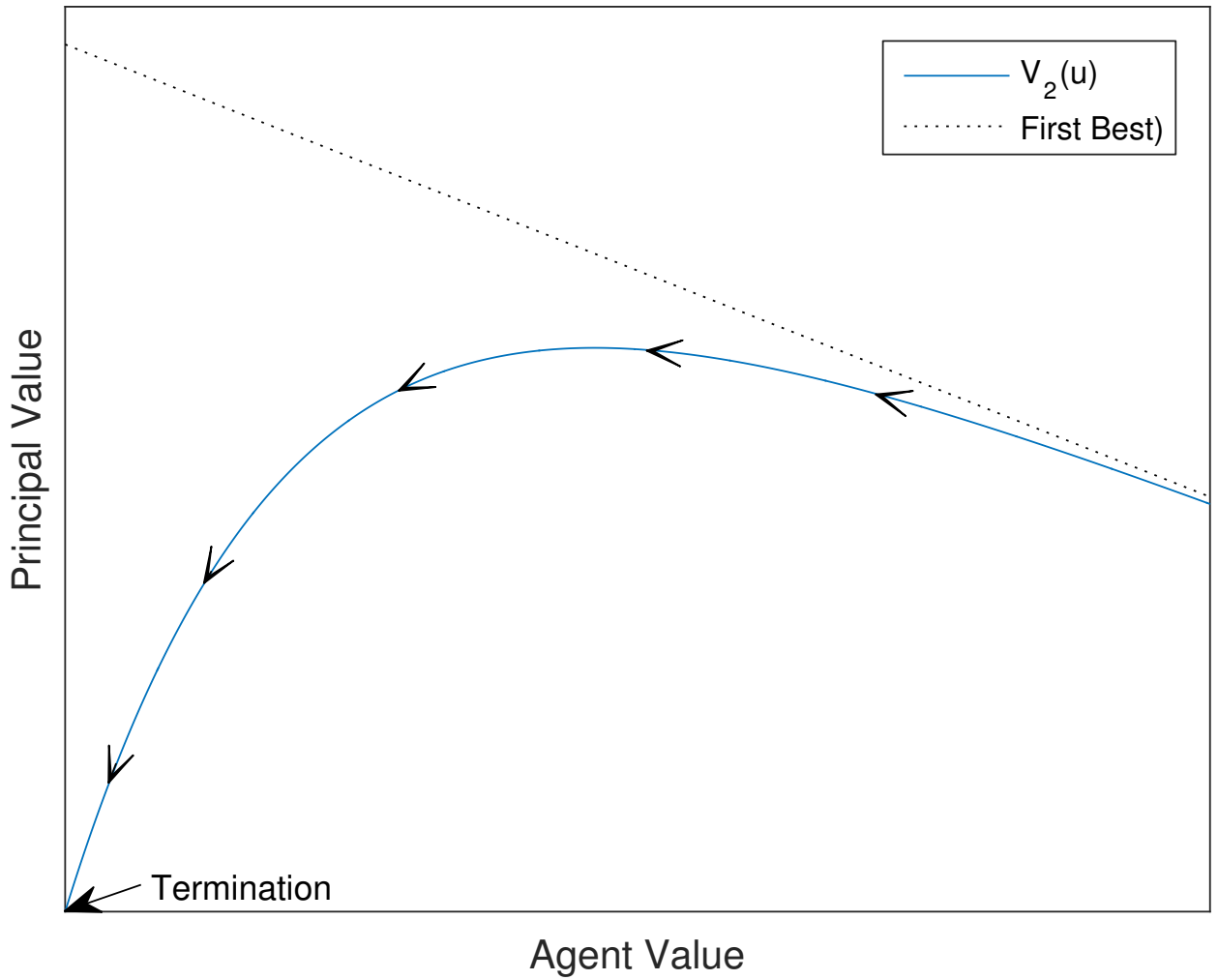
Solve by backward induction on the project stage

- State variable is a pair $(s, u) \in \{1, 2\} \times \mathbb{R}_+$
- $V_s(u)$ is P's value function in stage s
- Characterize optimum through dynamics of A's continuation value

NB: Already solved second stage problem, i.e.,

$$V_2(u) = V_{\text{one stage}}(u)$$

Second-stage payoff frontier



Agent continuation value decreases over time as deadline approaches.

First-stage problem

$$\lambda V_1(u) = \max_{R \geq 0} \lambda \overbrace{V_2(R)}^{\neq \Pi - R} - c + V_1'(u)\frac{du}{dt}$$

subject to

$$\lambda(R-u) \geq \phi, \tag{IC}$$

$$\frac{du}{dt} = -\lambda(R-u) \tag{PK}$$

$$V_1(0) = 0 \tag{BC}$$

Question: How much to "reward" the agent for a breakthrough in the first stage?

Solution to the first stage problem

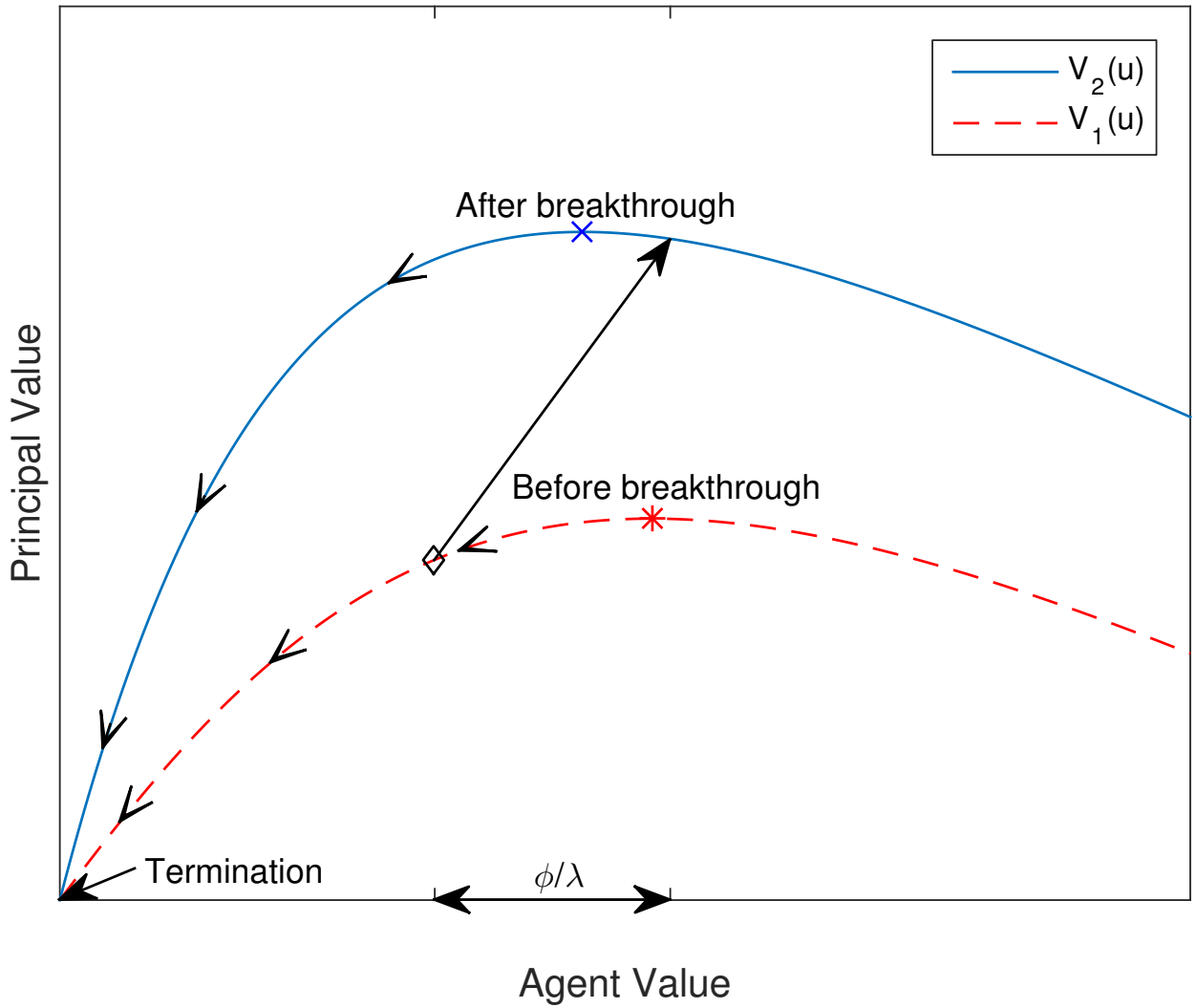
Two cases:

1. IC always binds in the first stage
   - $R(u) = u + \phi/\lambda$ for all u
   - Occurs when project benefits are *sufficiently large*

$$\Pi \geq \frac{2c}{\lambda}\left(\frac{e-1}{e-2}\right) \tag{C1}$$

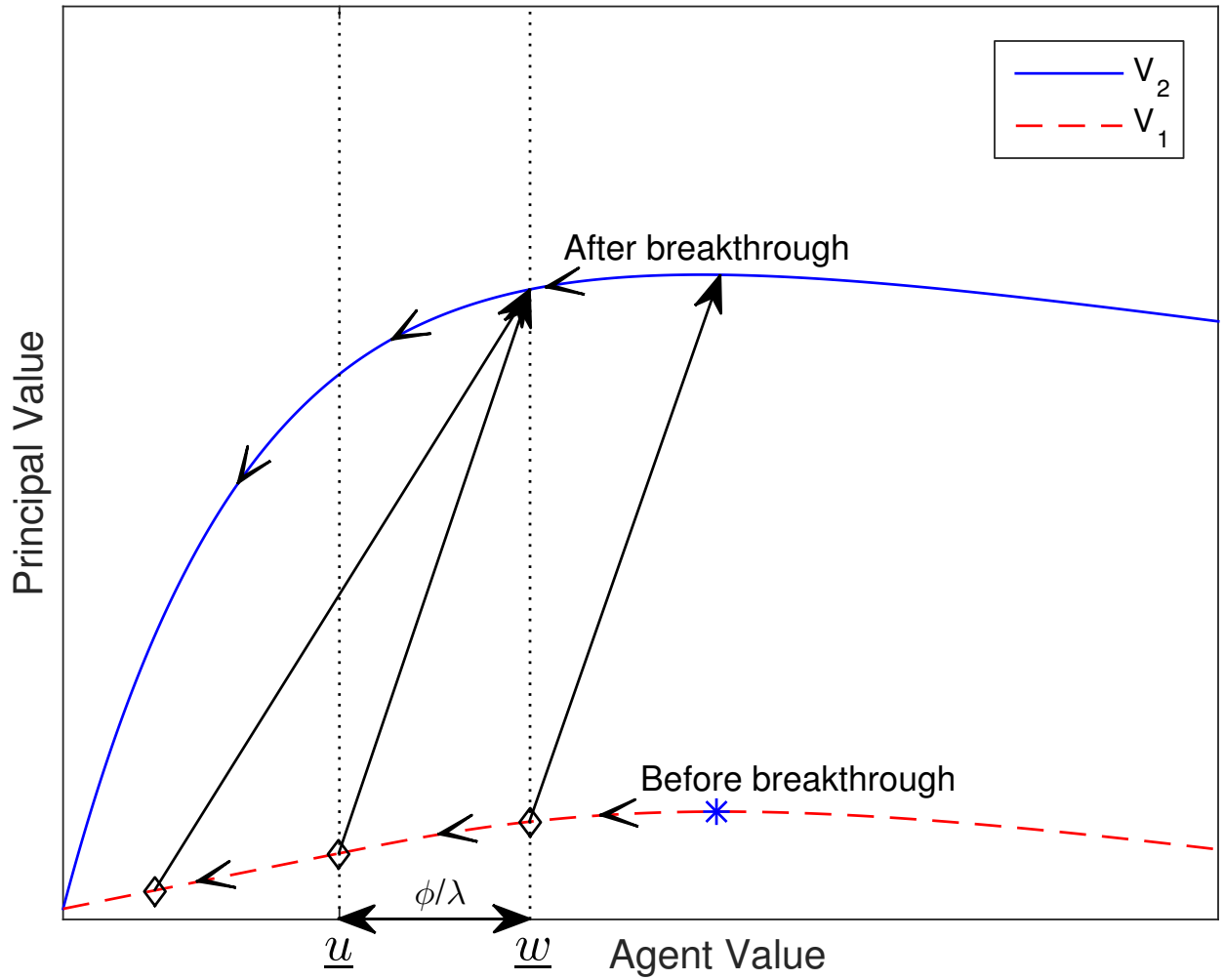
2. IC is slack for some u in the first stage
   - Occurs when project benefits are *moderate*, i.e., (C1) fails
   - Optimal to set $R(u) = \underline{w}$ for all $u \in [0, \underline{u}]$
   - Intuition?
     - P optimally shifts resources from first to second stage
     - Increase likelihood of termination in the first stage in order to preserve more time conditional on reaching the second

When project benefits are sufficiently large



Continuation value jumps up by ϕ/λ following a breakthrough regardless of when it occurs

When project benefits are moderate



Continuation value increases by more than ϕ/λ if $u < \bar{u}$

Summary

When project benefits are large, two "hard" deadlines, $T_1 < T_2$:

- If no breakthrough before T_1, project is terminated.
- If first breakthrough before T_1, A has until T_2 to make second breakthrough
  - Agent rewarded only if $\tau_2 \leq T_2$

Equivalent to one deadline with fixed "extension" for success

When benefits are moderate, the second deadline depends on τ_1

- If no breakthrough by t_s, the second clock is "paused" and restarted only after a breakthrough
- Regardless of $\tau_1 \in (t_s, T_1)$, the agent has the same amount of time to complete the second stage

Intangible progress

- The agent privately observes the first breakthrough
- The second breakthrough is still observable/contractible

A few observations:

1. Agent acquires (persistent) private information over time
   - Call the agent types A_1 (low) and A_2 (high)
2. The optimal contract with tangible progress would not induce truth telling
   - A_1 would falsely report breakthrough just before T_1
   - A_2 would hide a breakthrough and shirk for $t \in (t_s, T_1]$
3. A simple contract (independent of reports) would trivially induce truth telling..
   - But can the principal do better?

Why simple contracts are suboptimal

Lemma

For any contract with fixed deadline T and bounded reward scheme, there exists a Δ such that A_1 will shirk for all $t \in (T - \Delta, T]$.

Why?

- Probability of two breakthroughs proportional to Δ^2
- Shirking yields payoff proportional to Δ

But shirking is an inefficient form of compensation $(\phi \leq c)$

- Might as well just pay A_1 and terminate the project.

However, a severance payment is also not optimal...

Truthtelling constraints

By the revelation principle, can restrict attention to direct mechanisms in which the agent to reports progress truthfully and immediately.

- The truthtelling constraints take two forms

1. No False Progress (NFP): Agent does not want to falsely report a breakthrough.
2. No Hidden Progress (NHP): Agent does not want to "hide" a breakthrough.
    - Why hide progress? Think grant proposal...

Intangible progress $\Longrightarrow$ persistent private information

To formulate principal's problem recursively, need three state variables

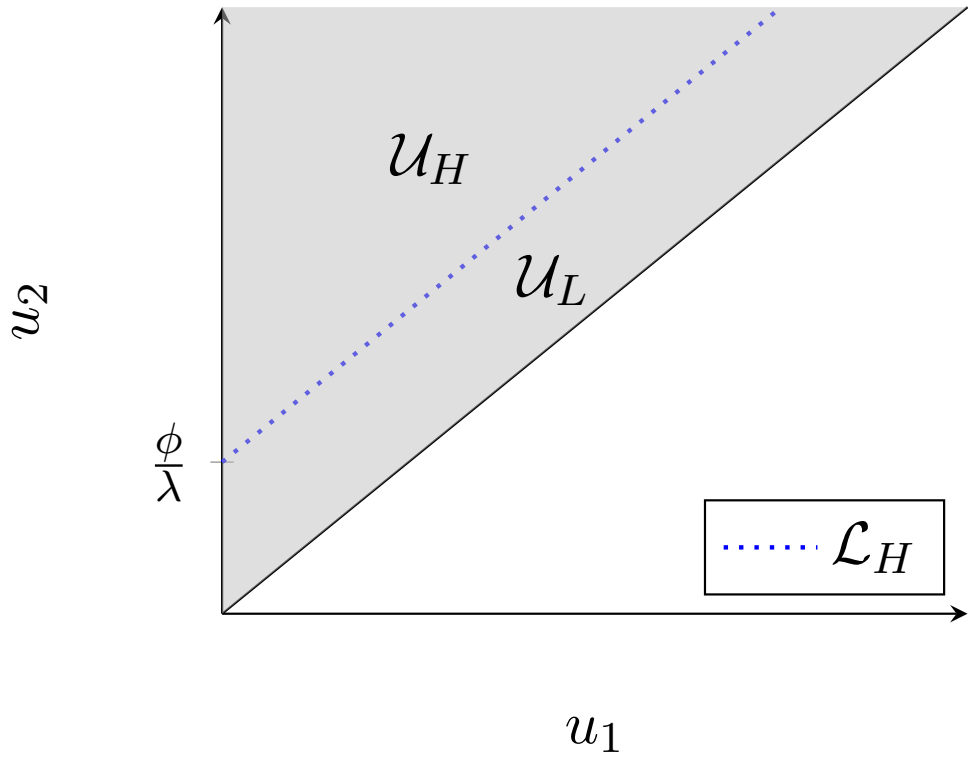
- s: Project stage (as reported by the agent)
- u_1: Promised utility to A_1
- u_2: Promised utility to A_2

With the extra state variable, we can take a similar approach to the case of tangible progress

- Solve the principal's problem by backward induction on s for any implementable utility pair (u_1, u_2).

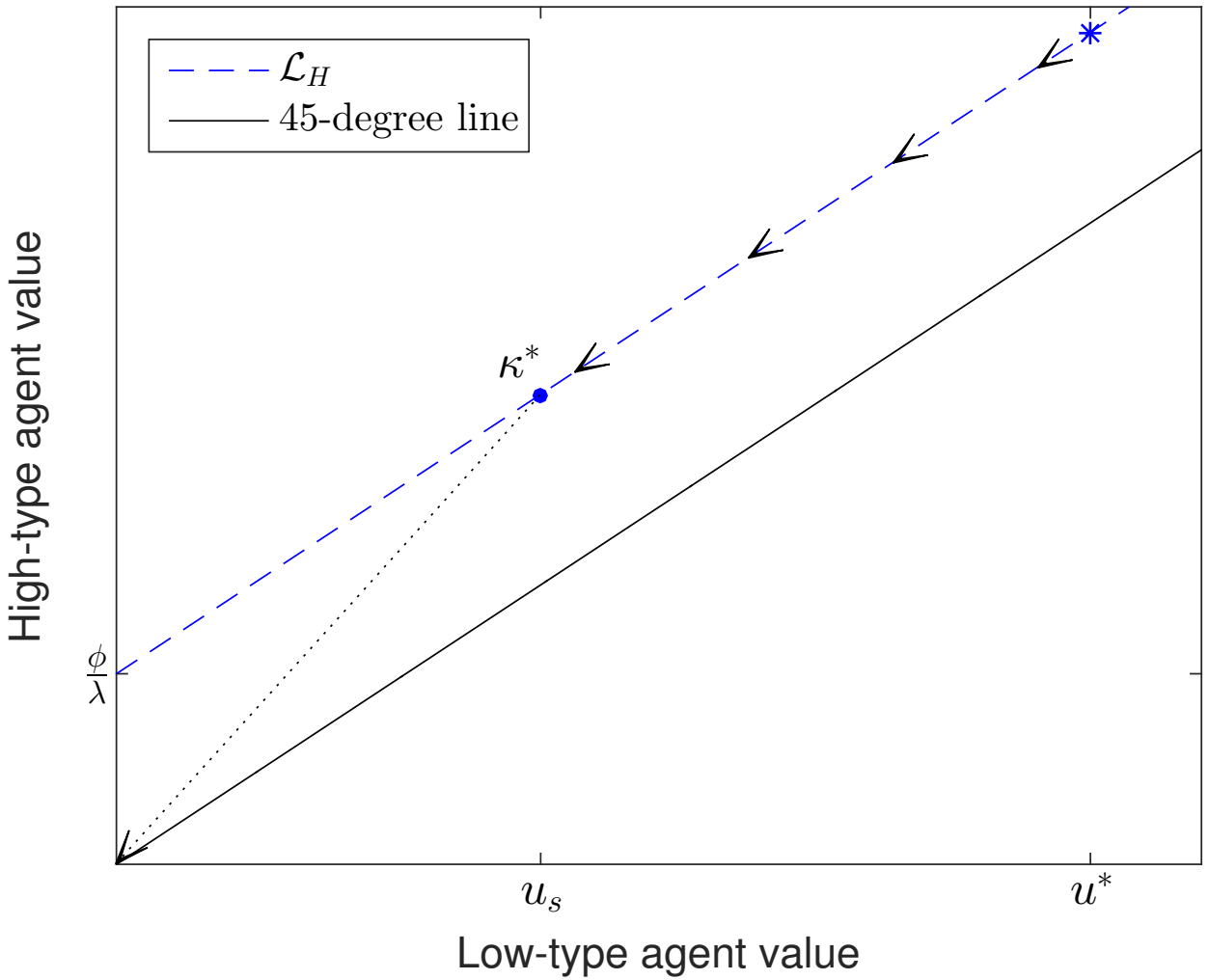
Implementable utility pairs

A_2 can always do at least as well as A_1



- Note that u_2 is the "reward" to A_1 for a breakthrough
- Hence, A_1 will shirk if state evolves in $\mathcal{U}_L$

Optimal dynamics prior to breakthrough



Continuation utilities drift down toward κ^*, communication prior to κ^* is not necessary.

What happens at κ^*?

Upon reaching κ^*, P asks: *"Have you made a breakthrough yet?"*

- If agent answers "yes"
  - Principal gives agent a relatively short deadline to make the final breakthrough.
- If agent answer "no"
  - Principal begins randomly terminating the project
  - Conditional on not terminating, state remains at κ^*

Interpretation: A "soft" deadline

- P guarantees funding until κ^*, but reserves the right to terminate thereafter if progress has not been reported
- Immediate communication is **critical** after the soft deadline

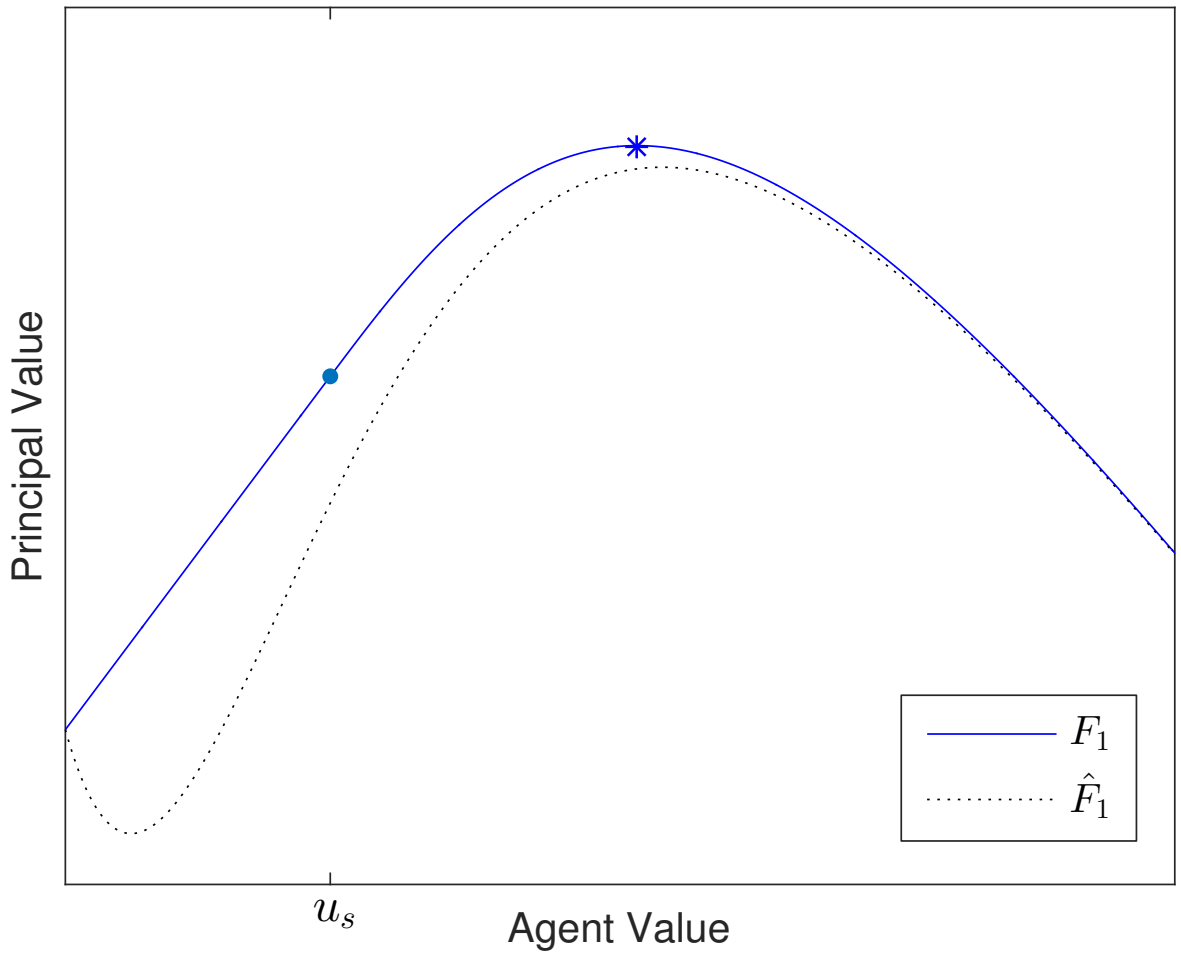
Intuition

Why is a soft deadline part of the optimal contract?

1. Why is it incentive compatible at κ^*?
   - A_2 likely to have ultimate success soon, does not want to risk termination
     $\implies$ strictly prefers truthtelling over the lottery (NHP slack).
   - A_1 is unlikely to succeed in near future, could "lie and steal" but weakly prefers the lottery by construction (NFP binds).

2. Why does the principal want to use it?
   - Needs to give A_1 utility of u_s **without increasing** CV after a breakthrough (NFP)
   - P would like to give **more time** after a breakthrough but cannot
   - Optimal to kill project today (with some prob) to preserve time following a breakthrough

More Intuition: Optimal vs Simple



- Additionally, agent will "run out of steam" as u_1 approaches zero under simple contract.

Payoffs, Welfare and Project Success

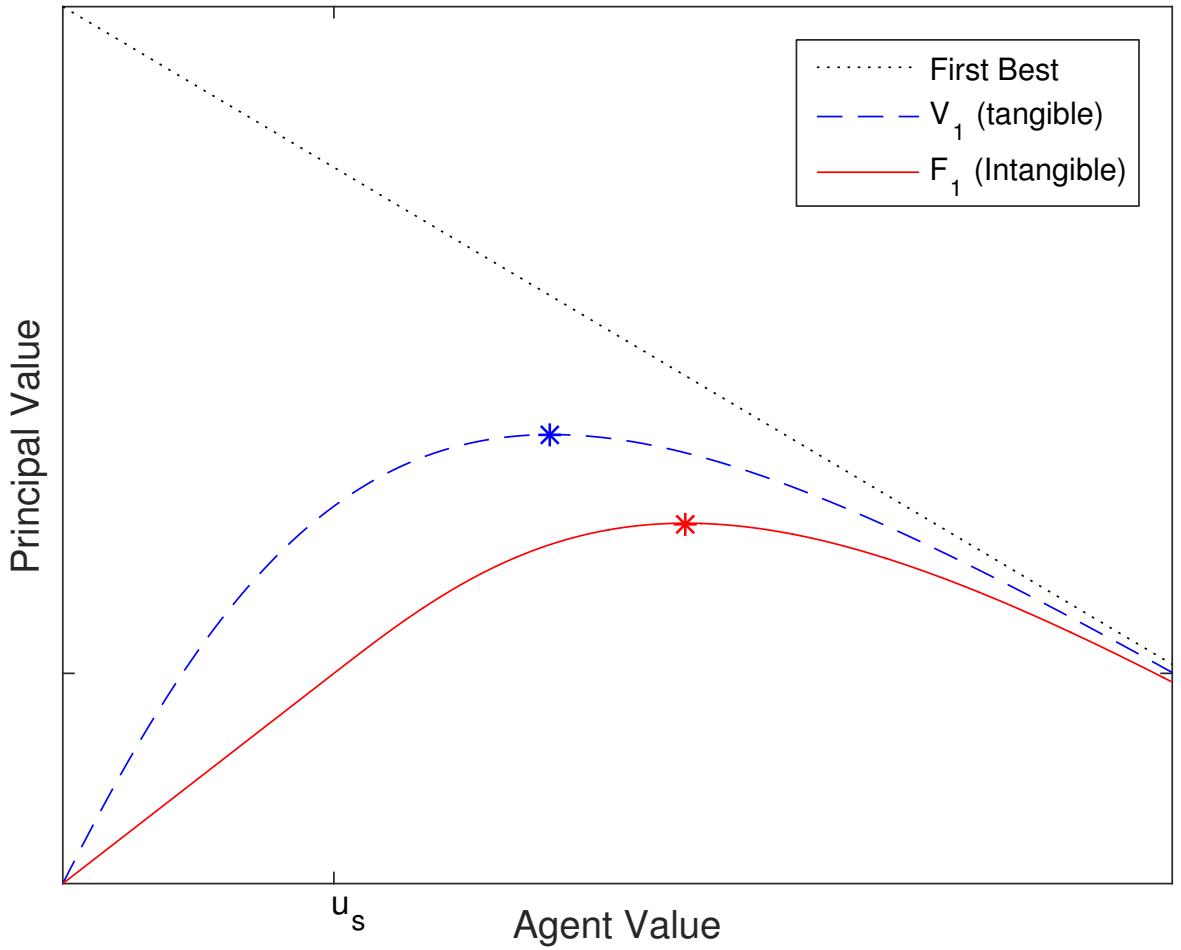
Question: How does the nature of progress affect payoffs and whether project succeeds?

Result

Under the P-optimal contract:

- The Principal does better with tangible progress
- The Agent gets more rents when progress is intangible
- The likelihood of project success (and total welfare) is higher with tangible progress

Tangible vs. Intangible



- Tangible: Principal does better, likelihood of success is higher
- Intangible: Agent earns more rents

Deadlines

Question: Should the agent be given more time to complete the first stage or the second stage?

With tangible progress:

- The amount of time the agent has to complete the second stage is larger than the amount of time to complete the first stage.
- Interpretation: *Short leash* then *longer leash* after progress

With intangible progress, we get exactly the opposite:

- P does not give A more *expected time* after a positive report
- *Long leash* then *short leash* structure is optimal

Asymmetric stages

In many relevant applications, one stage may be

- Expected to take more time (smaller λ)
- Require more working capital (higher c)
- More susceptible to diversion/shirking (higher ϕ)

To fix ideas, keep c and ϕ constant across stages and parameterize the asymmetry by $\alpha \in [-1, 1]$, where

$$\frac{1}{\lambda_1} = \frac{1+\alpha}{\lambda} \quad \text{and} \quad \frac{1}{\lambda_2} = \frac{1-\alpha}{\lambda}$$

- Maintains first-best project value at $\Pi - 2c/\lambda$ as α varies

Asymmetric stages

Result

With either type of progress, the principal's ex-ante payoff under the P-optimal contract is

- Increasing in α for α near 0
- Decreasing in α for α near 1
- Converges to one-stage project value as $\alpha \to 1$

Intuition

- On the margin, it is cheaper to compensate agent with promised utility in stage 2 rather than cash for ultimate breakthrough
- But as $\alpha \to 1$, monitoring technology becomes inferior

Implication: Optimal to make the first stage more difficult than the second stage (but not too much more difficult).

Costly reporting

Formal channels of communication often require the agent incur costs to documenting progress.

Question: Can the principal benefit by imposing reporting costs?

- Benefit: relaxes (NFP), can give more time after a positive report
- Cost: requires extra compensation to A_2

Result

Let ρ denote the cost incurred by the agent to report progress.

- A direct mechanism with $\rho > 0$ is inferior to one with $\rho = 0$.
- For ρ small, there exists an (indirect) mechanism in which P's payoff is higher than the optimal mechanism with $\rho = 0$.

Intuition: Only require reports after κ^*

Information suppression?

With intangible progress, P must give A rents to induce truth telling

- But P also uses this information to optimize termination policy

Question: Do these benefits outweigh the costs?

- If P cannot observe progress, restrict A's ability to do so?

Result

When τ_1 is unobservable to both P and A:

- The P-optimal contract can be implemented with a simple contract
- The principal is worse off than with intangible progress

Implication: Better to elicit information than try to suppress it

Conclusion

We study the provision of incentives in multistage projects

- Nature of progress is important
  - Tangible: Sequence of hard deadlines resembling staged financing
  - Intangible: Communication is valuable, optimal to use "soft" deadlines
- Implications for project design
  - Better to make first stage slightly harder
  - Costly reporting can be valuable
  - Better to elicit rather than suppress

More "progress" yet to be made...

- Limited commitment, implementation with financial securities, replacement, competition, continuous progress...