

Achieving Efficiency in Dynamic Contribution Games

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Motivation

- Team problems are ubiquitous in modern economies.
 - But such environments are susceptible to the free-rider problem.
 - Olson (1965), Hardin (1968), Alchian and Demsetz (1972), ...
- Collaboration is often geared towards achieving a particular objective.
 - *i.e.*, towards completing a “project”.
 - *Examples*: startups, joint R&D and new product development projects
- We study a model of dynamic contributions to a joint project.
 - Construct mechanism that implements efficiency as outcome of MPE.

Our Framework

- Model in a nutshell:
 - ① Ea. of n agents continually chooses his (costly) effort level $a_{i,t}$;
 - ② project progresses at a rate that depends on $\sum_i a_{i,t}$; and
 - ③ it generates a payoff once a prespecified amount of progress is made.
- *Stepping-stone*: Effort increases with progress.
 - Because the agents discount time & are rewarded upon completion.
 - *Implication*: efforts are strategic complements (across time).
- *Free-rider problem*: two kinds of inefficiency.
 - Ea. agent gets fraction of project's payoff \Rightarrow effort is inefficiently low.
 - Pos. externalities + str. complementarity \Rightarrow agents front-load effort.

Outline

- Efficient mechanism specifies:
 - Flow payments that increase with progress to *kill* front-loading.
 - Terminal rewards that make each agent the residual claimant.
 - Magnitude of flow payments chosen such that budget is balanced.
- *Relevance*: Mechanism resembles the incentives structure in startups.
 - Flow payments = salary differential btw market rate and actual salary.
 - As startup value increases, the value of outside option increases.
 - Initial employees receives shares (*i.e.*, residual claimants).
- Other Applications:
 - 1 Dynamic Extraction of an Exhaustible Common Resource.
 - 2 Strategic Experimentation.
 - More broadly, applicable to any dynamic game with externalities.

Related Literature

- **Moral Hazard in Teams:** Free-rider problem and restore efficiency
 - Holmström (1982): Budget breaker
 - Legros & Matthews (1993): Mixed strategies and unlimited liability
- **Dynamic Contribution / Experimentation Games:**
 - Admati & Perry (1991) ; Marx & Matthews (2000)
 - Georgiadis et. al. (2014) ; Georgiadis (2015)
 - Bonatti & Hörner (2011) ; Halac et. al. (2015)
- **Dynamic VCG:** Efficiency in dynamic games with private information
 - Bergemann and Välimäki (2010) ; Athey and Segal (2013)

Model Setup

- Team comprises of n agents. Agent i
 - is risk neutral and has cash reserves w_i ;
 - discounts time at rate $r > 0$;
 - *privately* exerts effort $a_{i,t}$ at cost $c_i(a)$, where $c'_i, c''_i, c'''_i \geq 0$; and
 - receives lump-sum $\alpha_i V$ upon completion of the project.
- Project starts at $q_0 = 0$, it evolves according to

$$dq_t = \left(\sum_{i=1}^n a_{i,t} \right) dt ,$$

and it is completed at the first time τ such that $q_\tau = Q$.

- Assume Markov strategies, *i.e.*, efforts at t depend only on q_t .

Building Blocks: Agents' Payoff Functions

- Agent i 's discounted payoff at t :

$$J_i(q_t) = e^{-r(\tau-t)} \alpha_i V - \int_t^\tau e^{-r(s-t)} c_i(a_{i,s}) ds$$

- Can write recursively as

$$rJ_i(q) = \max_{a_i} \left\{ -c_i(a_i) + \left(\sum_{j=1}^n a_j \right) J'_i(q) \right\}$$

subject to the boundary condition $J_i(Q) = \alpha_i V$.

- First order condition:

$$\underbrace{c'_i(a_i)}_{\text{marg. cost}} = \underbrace{J'_i(q)}_{\text{marg. benefit}}$$

- Write $a_i(q) = f_i(J'_i(q))$, where $f_i(\cdot) = c_i'^{-1}(\max\{0, \cdot\})$.

Markov Perfect Equilibrium: Characterization

- In a MPE, each agent's payoff function satisfies

$$rJ_i(q) = -c_i(f_i(J'_i(q))) + \left[\sum_{j=1}^n f_j(J'_j(q)) \right] J'_i(q)$$

subject to $J_i(Q) = \alpha_i V$ for all i .

Proposition 1. MPE Characterization

- The game has a unique project-completing MPE if Q is *small enough*.
 - Payoffs satisfy $J_i(q) > 0$, $J'_i(q) > 0$, and $J''_i(q) > 0$ for all i and q .
- $J''_i(q) > 0 \implies a'_i(q) > 0$, i.e., effort increases with progress.
 - Because agents discount time & are rewarded only upon completion.
 - Efforts are strategic complements in this game.

First-Best Outcome

- If efforts are chosen by a social planner, then her payoff satisfies

$$r\bar{S}(q) = \max_{a_1, \dots, a_n} \left\{ - \sum_{i=1}^n c_i(a_i) + \left(\sum_{i=1}^n a_i \right) \bar{S}'(q) \right\}$$

subject to $\bar{S}(Q) = V$.

- First order condition: $c'_i(a_i) = \bar{S}'(q) \implies \bar{a}_i(q) = f_i(\bar{S}'(q))$.

Proposition 2. First-Best Characterization

- 1 The social planner's problem admits a unique solution.
 - 2 $\bar{S}(q) > 0$, $\bar{S}'(q) > 0$, and $\bar{S}''(q) > 0$ for all q , if Q is *small enough*.
- Assume the project is socially desirable, *i.e.*, Q is *small enough*.

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Comparison: MPE vs First-Best

[▶ Details](#)

- *Two sources of inefficiency:* In the MPE,
 - ① the agents exert less effort ; and
 - ② they front-load their effort relative to first-best outcome.

- ① In the first-best (MPE), incentives are driven by V ($\alpha_i V < V$).
 - Because the agents ignore their externality on the other agents.

- ② Ea agent has incentives to front-load effort (*i.e.*, work harder early on) to induce others to raise future efforts, which renders him better off.
 - Due to positive externalities and strategic complementarity.
 - *Formally:* discounted marginal cost of effort (*i.e.*, $e^{-rt} c'_i(a_{i,t})$) \downarrow in t .

Outline

- We consider the set of mechanisms that specify:
 - Upfront payment $P_{i,0} \geq 0$ for ea. agent i due before work commences.
 - Schedule of flow payments $h_i(q_t) \geq 0$ due while project is in progress.
 - Reward \hat{V}_i upon completion of the project.
- ★ Payments are placed in a savings account accruing interest at rate r .
- *Objectives*: Efficiency, budget balance, individual rationality.
- Roadmap:
 - ① Assume $w_i = \infty$ for all i and characterize efficient mechanism.
 - ② Assume $w_i < \infty$ and provide conditions for implementability.
 - ③ Characterize optimal mechanism when conditions not satisfied.
 - ④ Extend the model to incorporate uncertainty & time-dependence.
 - ⑤ Other applications: resource extraction & strategic experimentation.

Incentivizing Efficient Actions

- Given set of flow payments $\{h_i(q)\}_{i=1}^n$, agent i 's payoff satisfies

$$r\hat{J}_i(q) = \max_{a_i} \left\{ -c_i(a_i) + \left(\sum_{j=1}^n a_j \right) \hat{J}'_i(q) - h_i(q) \right\}$$

- FOC: $c'_i(a_i) = \hat{J}'_i(q) \implies a_i(q) = f_i(\hat{J}'_i(q))$
- First-best FOC: $c'_i(a_i) = \bar{S}'(q)$
- For efforts to be efficient, we need: $\hat{J}'_i(q) = \bar{S}'(q)$ for all i and q .
- Therefore, $\hat{J}_i(q) = \bar{S}(q) - p_i$, where p_i is a constant TBD.
 - Upon completion, agent i must receive $\hat{J}_i(Q) = V - p_i$.

Flow Payments & Budget Balance

- Using $\hat{J}_i(\cdot)$ and $\bar{S}(\cdot)$, we back out agent i 's flow payment schedule

$$h_i(q) = \sum_{j \neq i} c_j (f_j(\bar{S}'(q))) + rp_i.$$

- Each agent i 's ex-ante discounted payoff is

$$\hat{J}_i(0) - P_{i,0} = \bar{S}(0) - (p_i + P_{i,0}).$$

- Budget balance requires that

$$\begin{aligned} \sum_{i=1}^n [\bar{S}(0) - (p_i + P_{i,0})] &= \bar{S}(0) \\ \implies \sum_{i=1}^n (P_{i,0} + p_i) &= (n-1)\bar{S}(0) \end{aligned}$$

Budget Balance

- How to pin down $\{P_{i,0}, p_i\}$?
- Total discounted cost of payments along the equilibrium path

$$e^{-r\bar{\tau}} \left[(n-1)V - \sum_{i=1}^n p_i \right]$$

- Minimized when $\sum_{i=1}^n p_i = (n-1)\bar{S}(0)$
- Henceforth, we set:
 - $P_{i,0} = 0$ for all i
 - $\{p_i\}$ such that

$$\sum_{i=1}^n p_i = (n-1)\bar{S}(0) \quad \text{and} \quad \hat{J}_i(q) = \bar{S}(q) - p_i \geq 0$$

An Efficiency Result

Proposition 4. Efficient Mechanism

Suppose that ea. agent i makes flow payments given by

$$h_i(q) = \sum_{j \neq i} c_j (f_j(\bar{S}'(q))) + rp_i,$$

and receives $V - p_i$ upon compl'n, where $\sum_{i=1}^n p_i = (n-1)\bar{S}(0)$. Then:

- \exists a MPE in which ea. agent i exerts the efficient effort $\bar{a}_i(q) \forall q$.
 - $h'_i(q) > 0$ for all i and q , i.e., flow payments are increasing in q .
 - The agents' total discounted payoff is equal to FB discounted payoff.
-
- Ea. agent is (essentially) made a full residual claimant.
 - $h_i(\cdot)$ increases at a rate s.t ea. agent's benefit from front-loading effort is offset by the cost associated with larger future flow payments.

A Problem (and a Solution)

- Mechanism in Proposition 4 is budget balanced on the eq'm path.
- Off the equilibrium path, if an agent deviates at some t , then the amount in the savings account at τ may be $\geq (n-1)V - \sum_{i=1}^n p_i$.
 - Unless 3rd party can pay ea. agent $V - p_i$, incentives will be affected.
- *Lemma*: Impossible to achieve budget-balance both on and off the equilibrium path. [▶ Details](#)

Corollary:

Consider previous mechanism, except upon completion, ea. agent receives $\min \{V - p_i, \beta_i (V + H_\tau)\}$. Efficiency properties of Prop. 4 are preserved.

- With strict budget balance, agents have incentives to shirk, let the balance grow, and collect a bigger reward upon completion.
- Capping ea. agent i 's reward at $V - p_i$ eliminates these incentives.

Uncertainty and Time Dependence

[Details](#)

- Assume that the project progresses according to

$$dq_t = \left(\sum_{i=1}^n a_{i,t} \right) dt + \sigma dW_t.$$

- Consider mechanisms that depend on both q and t .
 - i.e.*, flow payments $h_i(t, q)$ and terminal rewards $g_i(\tau)$.

Proposition 8:

For $h_i(t, q)$ and $g_i(\tau)$ as characterized, the following hold:

- There exists a MPE in which ea. agent exerts efficient effort level;
 - the agents' ex-ante discounted payoff = first-best payoff; and
 - the mechanism is ex-ante budget-balanced.
-
- With (Brownian) uncertainty, the agents must have unlimited cash, and there must be a 3rd party to balance the budget.

Dynamic Extraction of Common Resource

- **Model:**

- n agents extract a common resource. Stock is depleted according to

$$dq_t = - \sum_{i=1}^n a_{i,t} dt$$

where $q_0 > 0$, and game ends when $q_\tau = 0$.

- Ea. agent obtains flow utility $u_i(a_{i,t})$ from extracting at rate $a_{i,t}$.

- **Efficient mechanism** specifies that ea. agent receives subsidy

$$s_i(q) = \sum_{j \neq i} u_j(\bar{a}_j(q)) - rp_i,$$

where $\bar{a}_j(q)$ is the efficient extraction level.

- $s'_i(q) > 0$, i.e., subsidy decreases as resource becomes scarcer.
- Budget-balance via “participation” fee $P_{i,0}$ and choice of constant p_i .

Strategic Experimentation

Model: Keller, Rady and Cripps (2005) ; Bonatti & Hörner (2011)

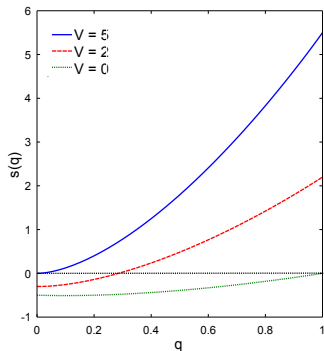
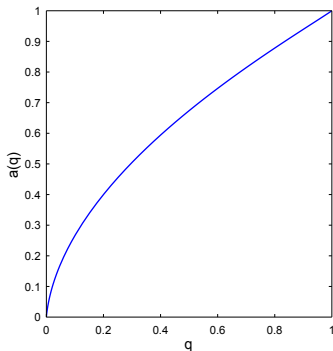
- Two arms: a *safe* arm with $\mathbb{E}[\text{flow payoff}] = 0$, and a *risky* arm.
 - If the risky arm is *bad*, then it never yields any payoff.
 - If it is *good*, then lump-sum payoff = 1 arrives $\sim Poi$ (exp. level).
- Ea. agent continuously chooses exp. level $a_{i,t}$ at flow cost $c_i(a_{i,t})$.
- *Belief Dynamics:*
 - Agents hold prior belief $q_0 = \Pr\{\text{risky arm is good}\}$.
 - As long as no arrival occurs, belief evolves according to

$$dq_t = -q_t(1 - q_t) \left(\sum_{i=1}^n a_{i,t} \right) dt$$

- Following a breakthrough, belief jumps to 1 and stays there forever.
- Assume that agents hold common belief p_t at all times.

Strategic Experimentation (Cont'd)

- Mechanism specifies for each agent:
 - prize V_i if he is the first to achieve a breakthrough, and
 - subsidy $s_i(q) = \sum_{k \neq i} [q(1 + V_i) \bar{a}_k(q) - c_k(\bar{a}_k(q))] + r(V_i - \gamma_i)$.
- Budget-balance (ex-ante) via “participation” fee $P_{i,0}$ and choice of V_i .



Wrapping Up

- We consider a dynamic contribution game, and propose a mechanism that induces agents to always choose the efficient actions in a MPE.
 - Specifies flow payments to eliminate front-loading incentives.
 - Terminal rewards that make ea. agent residual claimant.
 - Mechanism resembles features in incentive structures at startups.
- Mechanism can be adapted to other dynamic games w/ externalities.
 - 1 Dynamic extraction of a common resource
 - 2 Strategic experimentation
- Future work:
 - Optimal mechanism with uncertainty & cash constraints.
 - Efficient mechanism for generic dynamic game with externalities.

Comparison: MPE vs First-Best (1/3)

- *Two sources of inefficiency:* In the MPE,
 - 1 the agents exert less effort ; and
 - 2 they front-load their effort relative to first-best outcome.

Proposition 3:

- Assume the agents are symmetric, *i.e.*, $c_i(\cdot) = c_j(\cdot)$ and $\alpha_i = \alpha_j$.
 - Eq'm effort is inefficiently low, *i.e.*, $a_i(q) < \bar{a}_i(q)$ for all i and $q > \underline{q}$.
-
- In equilibrium, incentives are driven by $\alpha_j V < V$.
 - Because agents ignore their externality on the other agents.

Comparison: MPE vs First-Best (2/3)

- To demonstrate the front-loading effect, use the maximum principle of optimal control (which is equivalent to the HJB approach).

- Social Planner's Hamiltonian:

$$\bar{H}_t = - \sum_{i=1}^n e^{-rt} c_i(a_{i,t}) + \lambda_t^{fb} \left(\sum_{i=1}^n a_{i,t} \right)$$

- Optimality and adjoint equations are

$$\frac{d\bar{H}_t}{da_{i,t}} = 0 \quad \text{and} \quad \dot{\lambda}_t^{fb} = - \frac{dH_t}{dq},$$

or equivalently,

$$e^{-rt} c'_i(\bar{a}_{i,t}) = \lambda_t^{fb} \quad \text{and} \quad \dot{\lambda}_t^{fb} = 0$$

- Therefore, $e^{-rt} c'_i(\bar{a}_{i,t}) = \text{constant}$ for all t in the first-best outcome.
- Intuition:* Efficient to smooth efforts over time (because $c''_i > 0$).

Comparison: MPE vs First-Best (3/3)

[Return](#)

- Agent i 's Hamiltonian (MPE):

$$H_{i,t} = -e^{-rt} c_i(a_{i,t}) + \lambda_{i,t} \left(\sum_{j=1}^n a_{j,t} \right)$$

- Optimality equation: $e^{-rt} c'_i(a_{i,t}) = \lambda_{i,t}$
- Adjoint equation: $\dot{\lambda}_{i,t} = - \sum_{j \neq i} \frac{\lambda_{i,t} \dot{a}_{j,t}}{\sum_{l=1}^n a_{l,t}} < 0$
 - Inequality follows because $\lambda_{i,t} > 0$ and $a'_i(q) > 0 \Rightarrow \dot{a}_{j,t} > 0$.
- So $e^{-rt} c'_i(a_{i,t})$ decreases in t , *i.e.*, in MPE, agents front-load effort.
- *Intuition:* Each agent has incentives to front-load effort to induce others to raise future efforts (which renders him better off).

Strict Budget Balance

- Let

$$H_t = \sum_{i=1}^n \int_0^t e^{r(t-s)} h_i(q_s) ds$$

denote the balance in savings account at time t .

Lemma:

Suppose that ea. agent i receives $\beta_i (V + H_T)$ upon completion. Then:

- 1 \nexists no flow payment functions $h_i(\cdot)$ that lead to the efficient outcome.
- 2 Optimal mechanism is equivalent to mechanism w/ $\sum_{i=1}^n h_i(q) = 0$.

- Takeaways:
 - If we want efficiency, we must give up strict budget balance.
 - If we require $h_i \geq 0$ for all i , then mechanism becomes *powerless*.
- Second best?

Second Best

[▶ Return](#)

- Turns out a small modification suffices to ensure that
 - ① the mechanism is budget balanced on the eq'm path ; and
 - ② it never results in a budget deficit (but possibly a budget surplus).

Corollary:

Consider the previous mechanism, except upon completion, ea. agent receives $\min \{V - p_i, \beta_i (V + H_\tau)\}$, where $\beta_i = \frac{V - p_i}{V + (n-1)[V - \bar{S}(0)]}$.

- There exists a MPE in which ea. agent exerts the efficient effort level.
 - The agents' total discounted payoff is equal to FB discounted payoff.
-
- With strict budget balance, agents have incentives to shirk, let the balance grow, and collect a bigger reward upon completion.
 - Capping ea. agent i 's reward at $V - p_i$ eliminates these incentives.

Limited (but Sufficient) Cash Reserves

- Assume $h_i(\cdot)$'s are cash payments (as opposed to foregone income).
- Also assume that each agent has cash reserves $w_i < \infty$ at $t = 0$.
- Two challenges:
 - 1 Mechanism must specify what if an agent runs out of cash.
 - 2 Efficient mechanism may not be implementable.

Limited Cash Reserves: Implementability Condition

Proposition 5:

- The mechanism in Corollary is implementable iff $\exists \{p_i\}_{i=1}^n$ s.t

$$\sum_{i=1}^n p_i = (n-1) \bar{S}(0) \quad (\text{BB})$$

$$\int_0^{\bar{\tau}} e^{-rt} \sum_{j \neq i} c_j (f_j(\bar{S}'(q_t))) dt + p_i (1 - e^{-r\bar{\tau}}) \leq w_i \quad (\text{Cash})$$

$$0 \leq \bar{S}(0) - p_i \quad (\text{IR})$$

- If agents symmetric, implementable iff $w_i > e^{-r\bar{\tau}} \left(\frac{n-1}{n}\right) [V - \bar{S}(0)]$.

- Interpretation:

C.2. Each agent must have sufficient cash to make payments.

C.3. Each agent's IR constraint must be satisfied.

Limited Cash Reserves (Cont'd)

- Assume that an agent who runs out of cash, receives 0 upon completion, while others' rewards are unchanged.
- Define $l_i(q) = \mathbf{1}_{\{\text{agent } i \text{ has had cash at every } \tilde{q} < q\}}$

Proposition 6:

- Suppose that ea. agent i makes flow payments $h_i(q) l_i(q)$, and receives $\min\{V - p_i, \beta_i(V + H_\tau)\} l_i(Q)$ upon completion.
 - Assume that the conditions of Prop. 5 are satisfied.
 - Then the resulting mechanism implements the efficient outcome.
-
- *Intuition:*
 - Mechanism must punish agent who runs out of cash.
 - But his "share" cannot be distributed to the other agents.

Cash Constraints

- Efficient mechanism is implementable iff $w_i \geq \underline{w}_i$ for each i .
- What if the agents don't have sufficient cash reserves?
- Assuming symmetry, for arbitrary w , we characterize the mechanism that maximizes ex-ante total surplus.
- Optimal Mechanism:
 - Agents make payments while they still have cash.
 - Upon completion, they share balance in account + project payoff.
 - Similar properties as the efficient mechanism.

Uncertainty and Time Dependence: Setup

- We extend our model by
 - ① incorporating uncertainty in the evolution of the project:

$$dq_t = \left(\sum_{i=1}^n a_{i,t} \right) dt + \sigma dW_t, \text{ and}$$

- ② considering mechanisms that depend on both q and t .
 - *i.e.*, flow payments $h_i(t, q)$ and terminal rewards $g_i(\tau)$.
- Assume $w_i = \infty$ for all i .

First-Best Outcome

- The planner's problem satisfies

$$r\bar{S}(q) = \max_{a_1, \dots, a_n} \left\{ -\sum_{i=1}^n c_i(a_i) + \left(\sum_{i=1}^n a_i \right) \bar{S}'(q) + \frac{\sigma^2}{2} \bar{S}''(q) \right\}$$

subject to $\lim_{q \rightarrow -\infty} \bar{S}(q) = 0$ and $\bar{S}(Q) = V$.

- FOC: $c'_i(a_i) = \bar{S}'(q)$
- We know from Georgiadis (2015) that
 - the problem admits a unique solution ; and
 - effort increases with progress, *i.e.*, $a'_i(q) > 0$.

Analysis

- Agent i 's discounted payoff satisfies

$$rJ_i - J_{t,i} = \max_{a_i} \left\{ -c_i(a_i) + \left(\sum_{j=1}^n a_j \right) J_{q,i} + \frac{\sigma^2}{2} J_{qq,i} - h_i \right\}$$

subject to $\lim_{q \rightarrow -\infty} J_i(t, q) = 0$ and $J_i(t, Q) = g_i(t)$.

- FOC: $c'_i(a_i) = J_{q,i}(t, q)$
- Efficiency requires $J_{q,i}(t, q) = \bar{S}'(q)$ for all i, t, q .
- Therefore,

$$J_i(t, q) = \bar{S}(q) - p_i(t), \text{ where } p_i(t) = V - g_i(t)$$

Analysis (Cont'd)

- We now back out the flow payment functions

$$h_i(t, q) = \sum_{j \neq i} c_j (f_j(\bar{S}'(q))) + r(V - g_i(t)) + g_i'(t)$$

- Budget balance requires that

$$\sum_{i=1}^n J_i(0, 0) = \bar{S}(0) \implies \sum_{i=1}^n g_i(0) = nV - (n-1)\bar{S}(0)$$

- We pick $g_i(\cdot)$ such that $\mathbb{E}[h_i(t, q)] = 0$, and so we solve

$$0 = \sum_{j \neq i} \mathbb{E}[c_j (f_j(\bar{S}'(\bar{q}_t)))] + r(V - g_i(t)) + g_i'(t)$$

subject to $g_i(0)$, where $\sum_{i=1}^n g_i(0) = nV - (n-1)\bar{S}(0)$.

Efficient Mechanism

[▶ Return](#)

Proposition 8

Suppose ea. agent pays flow $h_i(t, q)$ and receives $g_i(\tau)$ upon completion.

- ① There exists a MPE in which ea. agent exerts efficient effort level;
- ② the agents' ex-ante discounted payoff = first-best payoff; and
- ③ the mechanism is ex-ante budget-balanced.

- With uncertainty, to achieve efficiency,
 - ① the agents must have unlimited cash; and
 - ② there must be a 3rd party to balance the budget.

Corollary

- Suppose that $\sigma = 0$, i.e., the project is deterministic.
- The efficient mechanism specifies 0 flow payments on the first-best path, and each agent receives $\alpha_i V$ upon completion.