# Firm Behavior During an Epidemic

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October 29, 2020

*Topics in Empirical Analysis and Economic Modeling Related to COVID-19*

*FGV EPGE*

# Introduction

- Ongoing COVID-19 outbreak has claimed more than one million lives
- Several economic and health impacts are related to firms
- Various policies targeting firms are being used worldwide
- Employee health is one of the main concerns of firms (Bartik et al., 2020)
- This paper: study labor allocation behavior of firms in an epidemic environment and how that can affect the dynamics of the disease

# This paper

Structural model of firm behavior and disease transmission

- Representative firm
  - Maximizes discounted profits
  - Workers $\rightarrow$ on-site, teleworking, furlhough, sick-leave
  - Infectious workers transmit disease in the workplace
    - Firm internalizes this
- General equilibrium
  - Distribution of workers across health statuses determine aggregate infectiousness
- Calibration: COVID-19 in the U.S.

# Preview of results

- Firm fights infections
  - Teleworking
  - Weekly rotation: on-site work $\leftrightarrow$ telework (two groups)
  - Flattens infection curve
- Subsidies to sick-leave reduce cost of sick worker $\rightarrow$ more deaths
- Furlough policies save lives
- Firm delays the fight against infection during economic downturns

# Literature

## Pre-COVID

- Theory
  - Kremer (1996), Chen et al. (2011), Toxvaerd (2019)
  - Infected agents impose negative externalities on susceptible by not internalizing the costs of transmission
- Quantitative
  - Chan et al. (2016), Greenwood et al. (2019)
  - The role of this externality in quantitative economic models of disease transmission
- Our contribution
  - Firms internalize some of these externalities...
  - ... with a different objective function (profits)

# Literature
## Post-COVID

- Structural models with COVID-19 transmission:
  - Alvarez et al. (2020), Acemoglu et al. (2020), Brotherhood et al. (2020a,b), Eichenbaum et al. (2020a,b), Glover et al. (2020), Guerrieri et al. (2020), Kaplan et al. (2020), and others
    - Optimal containment policies, importance of behavior, testing, macroeconomic stabilization policies...
    - Common aspect of all: focus on modeling workers
    - Our contribution: first paper modeling firms in an environment with disease transmission
- Empirical papers assessing impacts on firms:
  - Alfaro et al. (2020), Bartik et al. (2020), Ding et al. (2020), Fahlenbrach et al. (2020), Hassan et al. (2020)

# Model

- Time is discrete and runs forever
- Representative firm
- The firm chooses allocations of employees
- The workforce of the firm
  - On-site employees
  - Teleworking (remote) employees
  - Employees on leave (furloughed)
  - Employees on sick leave

# Model

- On-site employees are more productive than teleworkers
- The probability of catching COVID is higher for on-site employees than for teleworkers
- On-site infectious employees transmit COVID to susceptible on-site employees
- Firm takes workplace transmission into account
- Firm takes infection outside of the workplace as given
- Firm behavior generates aggregate infection (outside of the workplace) in equilibrium
- No hiring/firing (we plan adding this in an extension)

# Model

- Production function of firm is

$$f(n,h) = A(n+\gamma h)^{\alpha}, \quad A > 0,\ \alpha, \gamma \in (0,1) \tag{1}$$

  - $n$: mass of on-site workers
  - $h$: mass of teleworkers

- Per-period profit of the firm is

$$\pi(n,h,\ell,s) = f(n,h) - \delta_n wn - \delta_h wh - \delta_\ell w\ell - \delta_s ws \tag{2}$$

  - $\ell$: mass of workers on leave
  - $s$: mass of symptomatic sick workers
  - $\delta$: relative cost/policy parameters
  - $w$: wage, parameter

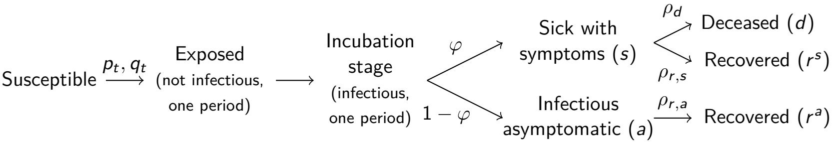
# World before the epidemic

- $N$: number of workers in the no-disease scenario

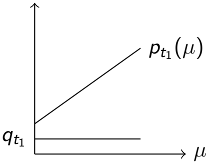
$$N = \underset{n}{\operatorname{argmax}}\, An^{\alpha} - \delta_n wn \tag{3}$$

- Disease arrives unexpectedly
- No hiring/firing after disease arrives

# Infections and health stages




- $q_t$: probability of an employee getting infected if not on-site in $t$
- $p_t(\mu)$: probability of infection in $t$ if on-site and there are $\mu$ infectious on-site employees



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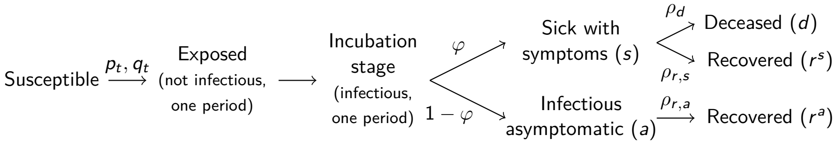


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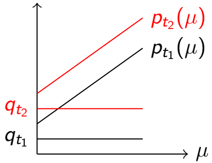

# Human resources by health status

- Firm observes four groups of workers:
  1. Deceased
  2. Sick symptomatic
  3. Recovered symptomatic
  4. Employees with uncertain health status
     - 4.1 Susceptible
     - 4.2 Incubated infection
     - 4.3 Infectious asymptomatic
     - 4.4 Recovered asymptomatic

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  2. Sick symptomatic
  3. Recovered symptomatic
  4. Employees with uncertain health status $\begin{cases} \text{on-site in } t-1 \\ \text{not on-site in } t-1 \end{cases}$
     - 4.1 Susceptible
     - 4.2 Incubated infection
     - 4.3 Infectious asymptomatic
     - 4.4 Recovered asymptomatic

Which groups can the firm manage?

# Firm's choices

| | | On-site in $t$ | Teleworker in $t$ | Leave in $t$ |
|---|---|---|---|---|
| Uncertain status | On-site in $t-1$ | $n_t^n$ | $h_t^n$ | $\ell_t^n$ |
| | Not on-site in $t-1$ | $n_t^m$ | $h_t^m$ | $\ell_t^m$ |
| | Recovered workers | $n_t^r$ | $h_t^r$ | $\ell_t^r$ |

# Laws of motion

$$d_{t+1} = d_t + \rho_d s_t \tag{4}$$
$$r^s_{t+1} = r^s_t + (1 - \rho_d)\rho_{r,s} s_t \tag{5}$$
$$r^a_{t+1} = r^a_t + \rho_{r,a} a_t \tag{6}$$
$$s_{t+1} = (1 - \rho_d)(1 - \rho_{r,s}) s_t + \varphi(\tilde{n}_t + \tilde{m}_t) \tag{7}$$
$$a_{t+1} = (1 - \rho_{r,a}) a_t + (1 - \varphi)(\tilde{n}_t + \tilde{m}_t) \tag{8}$$

- $\tilde{n}_t$: on-site employees with incubated infection in $t$
- $\tilde{m}_t$: out of workplace employees with incubated infection in $t$

- $a_{n,t}$: on-site asymptomatic employees (infectious) in $t$

$$a_{n,t} = (n_t^n + n_t^m)\frac{a_t}{N - r_t^s - s_t - d_t} \tag{9}$$

- Probability of infection of on-site employees

$$p_t = \min\left\{\Pi_{p,q} q_t + \Pi_{p,n}(\tilde{n}_t + a_{n,t}), 1\right\} \tag{10}$$

  where $\Pi_{p,q} \geq 1$ and $\Pi_{p,n} > 0$
- $c_t$: fraction of susceptible among uncertain workers in $t-1$

$$c_{t-1} = 1 - \frac{r_t^a + a_t}{N - r_t^s - s_t - d_t} \tag{11}$$

- Laws of motion for $\tilde{n}_t$ and $\tilde{m}_t$

$$\tilde{n}_t = n_t^n c_{t-1} p_{t-1} + n_t^m c_{t-1} q_{t-1} \tag{12}$$
$$\tilde{m}_t = m_t^n c_{t-1} p_{t-1} + m_t^m c_{t-1} q_{t-1} \tag{13}$$

# Constraints

- Workers in each group must be split among available options:

$$n_t^n + h_t^n + \ell_t^n = n_{t-1}^n + n_{t-1}^m - \varphi \tilde{n}_{t-1} \tag{14}$$
$$n_t^m + h_t^m + \ell_t^m = h_{t-1}^n + \ell_{t-1}^n + h_{t-1}^m + \ell_{t-1}^m - \varphi \tilde{m}_{t-1} \tag{15}$$
$$n_t^r + h_t^r + \ell_t^r = r_t^s \tag{16}$$

- Initial conditions:

$$n_{-1}^n = N, \quad \tilde{n}_{-1} = \varepsilon \tag{17}$$

  all else zero
- $\varepsilon$: initial mass of infected workers

# Firm's problem

- Firm maximizes
$$\sum_{t=0}^{\infty} \beta^t \pi_t \tag{18}$$
subject to constraints and laws of motion
- Choice variables:
$$n_t^n, h_t^n, \ell_t^n, n_t^m, h_t^m, \ell_t^m, n_t^r, h_t^r, \ell_t^r \geq 0 \quad \forall t \tag{19}$$

# Two-stage problem

- All dynamic equations that depend on $h$ and $\ell$ only depend on these variables through $h + \ell \equiv m$.
- Static problem: for a given $n$ and $m$,

$$\max_{h,\ell \geq 0} A(n + \gamma h)^{\alpha} - \delta_n wn - \delta_h wh - \delta_\ell w\ell - \delta_s ws \tag{20}$$

$$\text{subject to } h + \ell = m \tag{21}$$

- Choice variables of dynamic problem:

$$n_t^n, m_t^n, n_t^m, m_t^m, n_t^r, m_t^r \geq 0 \quad \forall t \tag{22}$$

# General equilibrium

- Firm takes as given the path of $q_t$
- $q_t$ is determined in equilibrium by the firm's choices

$$q_t = \Pi_q(\tilde{n}_t + \tilde{m}_t + a_t) \tag{23}$$

where $\Pi_q > 0$

# Features of the model

- The epidemic has negatives effects on the output and profits of the firm
  - The workforce of the firm shrinks because employees catch infection and take a sick leave
  - This reduces the output and profits since $\delta_s > 0$ and the firm cannot achieve its optimal size
  - The workforce of the firm is also smaller after the culmination of the epidemic because of deaths among workers
  - This also reduces output and profits
- The firm allocates all known recovered employees into on-site work given that $\gamma < 1$
  - Add concavity

# Features of the model: teleworking and rotation

- The firm wants to allocate employees into teleworking and leave in times of an epidemic
  - These reduce $p_t$ and infections among all employees given that $p_t \geq q_t$
- Dynamic trade-off:
  - Allocate employees into teleworking and leave and have current output loss vs. have higher output later and pay employees on sick leave
- The firm has incentive to rotate employees between on-site work and either teleworking or leave
  - Employees who were working on-site previously have higher chances of being infectious than employees who were either teleworking or on leave in previous periods
- All these incentives are stronger for higher values of the ratio $p_t/q_t$

# Calibration

| Parameter | Value | Comment |
|---|---|---|
| **Panel A. Firm** | | |
| $A$ | 1 | Normalization |
| $N$ | 1 | Normalization |
| $\alpha$ | 0.7 | Labor share of revenues |
| $\beta$ | $0.96^{1/52}$ | Time discount (weekly) |
| $\gamma$ | 0.9 | $\approx$ 30% teleworkers at peak (Brynjolfsson et al., 2020) |
| $w$ | 0.7 | Wage is such that optimal $N = 1$ in no disease/epidemic times |
| $\delta_n, \delta_h, \delta_\ell, \delta_s$ | 1 | Policy parameters |
| **Panel B. COVID-19** | | |
| $\rho_{r,s}$ | 1/3.52 | Average duration of hospitalization (Verity et al., 2020) |
| $\rho_{r,a}$ | 1/3.52 | Same as $\rho_{r,s}$ |
| $\rho_d$ | 0.00202 | Probability of death conditional on hospitalization (CDC, 2020) |
| $\Pi_q$ | 0.25 | $R_0 = 2.5$ |
| $\Pi_{p,q}$ | 1 | No discontinuity from $q$ to $p$ |
| $\Pi_{p,n}$ | 0.6667 | $\approx$ 70% of infections in the workplace (Ferguson et al., 2006) |
| $\varphi$ | 0.5 | Proportion of asymptomatic, range: 4%-75% (CEBM, 2020) |
| $\varepsilon$ | 0.001 | 0.1% infected workers in first period |
| **Panel C. Time** | | |
| Time period | 1 week | |
| Epidemic end | 3 years | In almost all simulations the epidemic nearly ends in 1 year (herd immunity) |

# Results

Figure: The dynamics of the epidemic

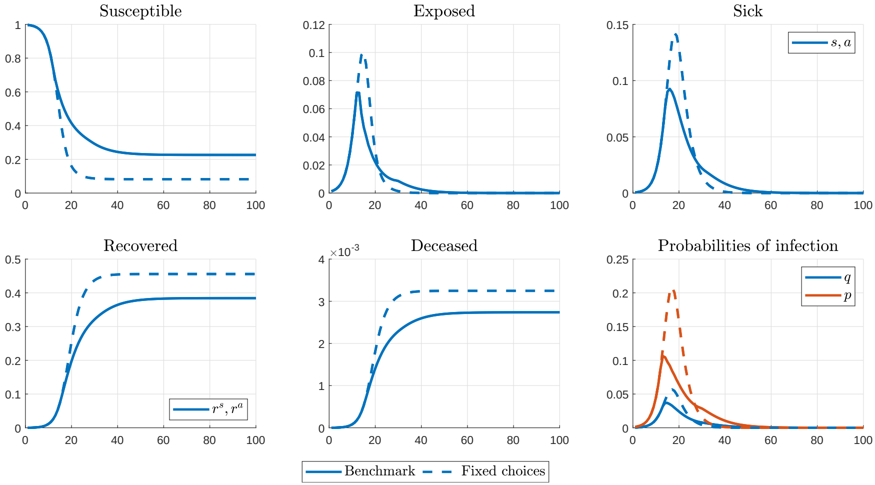
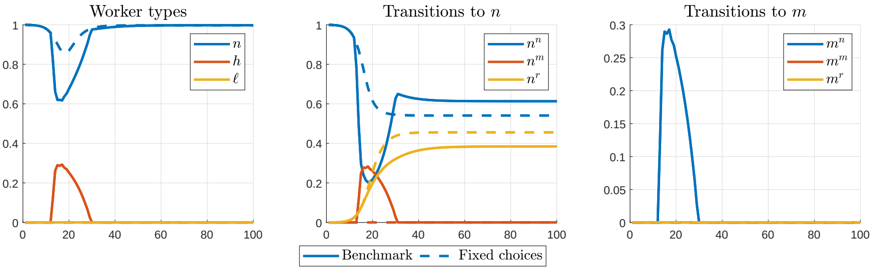


Figure: The dynamics of employee allocations during the epidemic



## Table: Main results

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| | | Fixed | Teleworking | | Sick leave | | Leave |
| | Benchmark | choices | $\gamma = 0.98$ | $\delta_h = 0.97$ | $\delta_s = 0$ | $\delta_s = 1.5$ | $\delta_\ell = 0$ |
| Weeks to the peak | 14 | 17 | 15 | 15 | 17 | 14 | 16 |
| Sick at the peak (%) | 9.31 | 14.25 | 5.95 | 6.04 | 14.25 | 7.15 | 7.58 |
| Deceased (%) | 0.27 | 0.32 | 0.25 | 0.25 | 0.32 | 0.26 | 0.26 |
| Deceased (%Δ w.r.t. BM) | 0.00 | 18.41 | -8.73 | -8.82 | 18.41 | -5.64 | -5.53 |
| Recovered (%) | 77.25 | 91.47 | 70.50 | 70.44 | 91.47 | 72.89 | 72.98 |
| Recovered (%Δ w.r.t. BM) | 0.00 | 18.41 | -8.73 | -8.82 | 18.41 | -5.64 | -5.53 |
| Production 1 year (%Δ w.r.t. ND) | -2.17 | -2.34 | -1.83 | -2.12 | -2.34 | -2.13 | -6.81 |
| Production 1 year (%Δ w.r.t. BM) | 0.00 | -0.17 | 0.34 | 0.05 | -0.17 | 0.04 | -4.75 |
| Discounted profits | 381.24 | 381.17 | 381.31 | 381.31 | 382.28 | 380.78 | 381.27 |
| Discounted profits (%Δ w.r.t. ND) | -0.28 | -0.29 | -0.26 | -0.26 | 0.00 | -0.40 | -0.27 |
| Discounted profits (%Δ w.r.t. BM) | 0.00 | -0.02 | 0.02 | 0.02 | 0.27 | -0.12 | 0.01 |
| Profits 1 year (%Δ w.r.t. ND) | -6.85 | -7.32 | -5.81 | -5.83 | -0.11 | -9.54 | -6.58 |
| Profits 1 year (%Δ w.r.t. BM) | 0.00 | -0.50 | 1.12 | 1.10 | 7.24 | -2.89 | 0.30 |
| Max. teleworking (%) | 29.26 | 0.00 | 33.51 | 33.65 | 0.00 | 33.35 | 24.06 |
| Max. leave (%) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 12.05 |
| Max. $n$ to $m$ (%) | 29.26 | 0.00 | 33.51 | 33.65 | 0.00 | 33.35 | 31.02 |
| Max. $m$ to $n$ (%) | 28.28 | 0.00 | 32.70 | 32.77 | 0.00 | 32.39 | 30.12 |
| Sum $n$ to $m$ | 3.32 | 0.00 | 7.23 | 7.12 | 0.00 | 5.29 | 5.94 |
| Sum $m$ to $n$ | 3.23 | 0.00 | 7.12 | 7.01 | 0.00 | 5.19 | 5.84 |

*Notes:* "BM": benchmark. "ND": no-disease.

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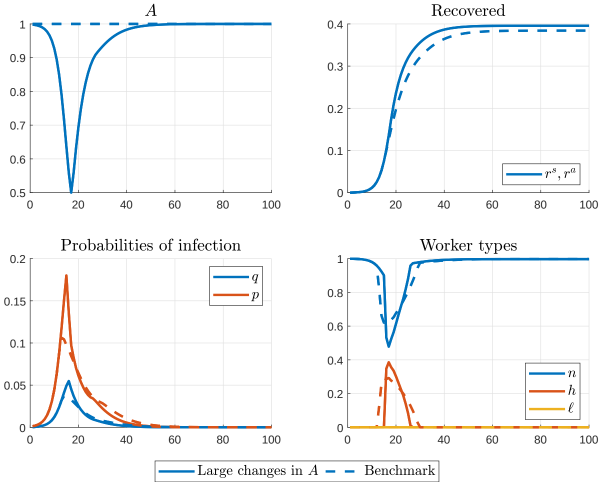
# Lockdowns, production restrictions, and changes in the demand

- Reduced form approach for lockdowns, fall in demand
- If more sick individuals, lower demand:

$$A_t = 1 - \delta_A s_t \tag{24}$$

## Figure: Changes in $A$



# Firm delays the fight against infections during the economic downturn. Why?

- Wrong conjecture:

  Demand is lower

  $\Rightarrow$ The productivity loss of teleworking doesn't hurt the firm as much

  $\Rightarrow$ Firm protects workers

- What actually happens:
  - Revenue brought by on-site/teleworker doesn't vary across time:

$$\frac{\text{On-site worker production in } t}{\text{Teleworker production in } t} = \frac{A_t \times 1}{A_t \times \gamma} = \frac{1}{\gamma} \tag{25}$$

  - Opportunity cost of having a sick worker changes over time:

$$\text{Foregone revenue per worker in } t = A_t \text{ (or } A_t \gamma) \tag{26}$$

# Firm delays the fight against infections during the economic downturn. Why?

- Opportunity cost of sick worker falls in the COVID outbreak
- Disease is not so deadly for young workers
- Firm wants recovered workers when demand starts moving up
- Firm prefers infections in the beginning rather than in the end

# Next steps

- Modeling firing and hiring is done
- Planner's problem

# Planner's problem

$$\text{Objective function: } \sum_{t=0}^{\infty} \beta^t \left[ f(n_t, h_t) - \delta_d (d_t - d_{t-1}) \right] \qquad (27)$$

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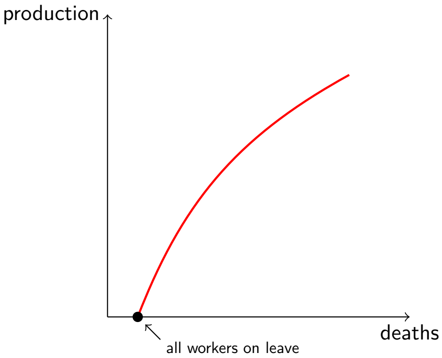

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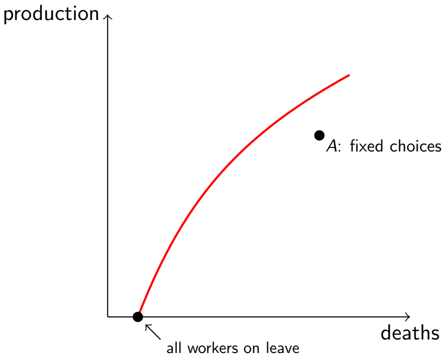

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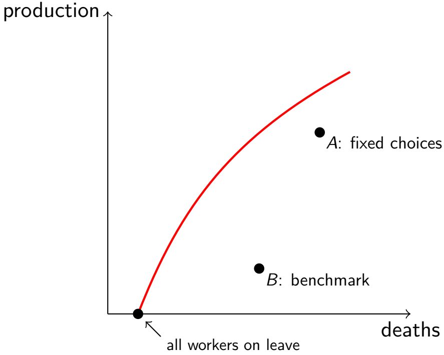

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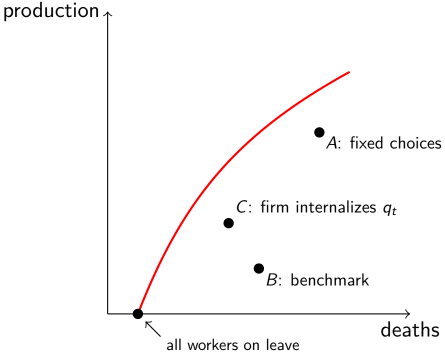

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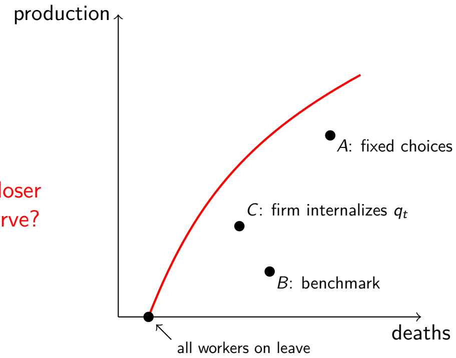


How policies can lead to equilibria closer to the planner's curve?

# Conclusions

- We derive a novel model in which a representative firm operates in an epidemic environment and internalizes the costs of disease transmission
- We calibrate this model to match the properties of the COVID-19 epidemic
  - The fight against infections in firms has significant effect on the dynamics of the epidemic
  - This fight bears benefits for firms in terms of profits and output albeit these gains might not be large
  - Policies subsidizing teleworking, affecting sick leave and temporary leave payments can have significant effects on the dynamics of the epidemic
  - Firms delay and weaken the fight against infections during economic downturns
- Further work:
  - Hiring and firing, social planner, concavity, calibration, further comparative statics (e.g., $\varphi$)

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