

An Introduction to the Heterogeneous Agents Resources and toolKit

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Minicourse

“Hands-On Heterogeneous Agent Macroeconomics”

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Agenda: A Flavor of HARK

1. “Microeconomic” models in HARK: the `AgentType` class
2. Example HARK model
 - ▶ Consumption with permanent and transitory shocks to income
3. 30,000 foot view: What else is in HARK?

Microeconomic Models in HARK

- ▶ Concern decision-making of one agent
- ▶ Discrete time
- ▶ Sequence of choices
 - ▶ Household: Consumption, labor supply, portfolio choice, etc
 - ▶ Firm: Investment, Employment, R&D, ...
- ▶ Agents treat inputs to problem as *exogenous*

Key restriction: Essentially, Bellman equation

Model solution can be constructed as iteration on sequence of “one period problems,” conditional on solution to subsequent period.

Two kinds of heterogeneity

- ▶ *Ex post* heterogeneity: Agents differ because a different sequence of events or shocks has happened to them
 - ▶ Luck of the draw
- ▶ *Ex ante* heterogeneity: Agents differ in objectives, preferences, expectations, etc before anything “happens” to them
 - ▶ Some people are more risk averse than others, e.g.

Crash Course in Object-Oriented Programming

(For more, see WhyPython)

- ▶ Traditional programming is *procedural*:
 - ▶ Accomplish task step by step; intuitive
- ▶ Python is an *object-oriented* language:
 - ⇒ conceptual (and operational) groupings of similar things
 - ▶ Start by defining needed items as a *class*
 - ▶ Example of a “class”: `PerfForesightConsumerType`
 - ▶ **Attributes**: What characteristics define one *instance*?
 - ▶ e.g., an instance of a `PerfForesightConsumerType` with $\{R, \beta, \dots\} = \{1.05, 1/1.05, \dots\}$
 - ▶ **Methods**: What actions can instances of the class “do”?
 - ▶ e.g., calculate ‘impatience’ implied by its parameter values

HARK's "Master Class": AgentType

- ▶ General purpose class for representing economic agents
- ▶ Each model creates a subclass of AgentType
 - ▶ e.g. PerfForesightConsumerType is an AgentType subclass
 - ▶ Includes attributes, functions, and methods...
 - ▶ All AgentType subclasses have a solve() method
 - ▶ Common structure \Rightarrow different models "play nicely" together
 - ▶ Even though guts of solve() method differ for each subclass
 - ▶ Much easier to compare and exchange models
- ▶ Complex models extend basic ones through "class inheritance"

Defining An Agent's Problem

- ▶ Define Behavior in some “Terminal Period”
 - ▶ Created by the class's method `solveTerminal`
 - ▶ Example that can be used for finite or infinite horizon:
 - ▶ `solution_terminal.cFunc = consume everything`
 - ▶ `solution_terminal.vPfunc = u'(consume everything)`
- ▶ Define Information needed to solve one period back
 - ▶ Variables, Distributions, Parameters, ...
- ▶ Keep Going ...
 - ▶ Life Cycle? To birth
 - ▶ Infinite Horizon? To convergence
 - ▶ Infinite Horizon with Seasons? To seasonal convergence
 - ▶ ...

Defining An Agent's Problem

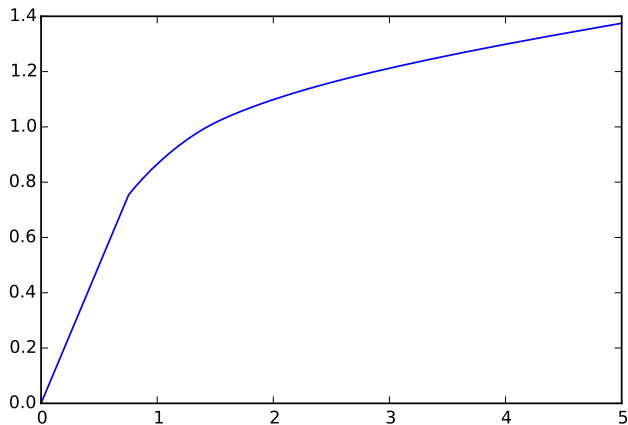
- ▶ Example: IndShockConsumerType consumption model:
 - ▶ $CRRA = 3.2$
 - ▶ $DiscFac = 0.96$
 - ▶ $Rfree = 1.03$
 - ▶ $IncomeDstn = [too\ much\ to\ put\ here]$
 - ▶ Life Cycle version:
 - ▶ $PermGroFac = [1.005, \dots, 1.005, 0.4, 0.998, \dots, 0.998]$
 - ▶ $LivPrb = [1, \dots, 1, 0.997, 0.994, 0.991, \dots, 0]$
 - ▶ Infinite Horizon version:
 - ▶ $PermGroFac = [1.02]$
 - ▶ $LivPrb = [0.98]$

Workhorse: Buffer Stock Consumption Model

Class IndShockConsumerType

- ▶ Inherits attributes of PerfForesightConsumerType
 - ▶ Geometric discounting β per period
 - ▶ One choice: How much to consume vs save
 - ▶ CRRA utility from consumption
 - ▶ Exogenous interest factor for asset returns
- ▶ Adds assumptions about income uncertainty and constraints
 - ▶ Mathematical Details: Formal model

Buffer Stock Model Consumption Function



Horizontal Axis: "Money"; Vertical Axis: "Spending"

What Else Is In HARK or the Econ-ARK?

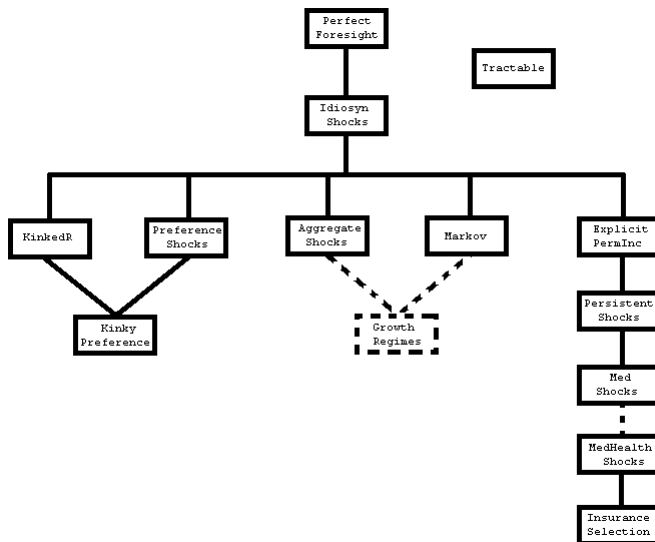
- ▶ General purpose tools for generating and representing distributions, interpolated functions, etc
- ▶ Tools for estimation / optimization (fairly sparse)
- ▶ Framework for “macroeconomic” models: Market class
- ▶ Several extensions of basic consumption-saving model
- ▶ Some small demonstration exercises
- ▶ All results from several papers:
 - ▶ “The Distribution of Wealth and the Marginal Propensity to Consume” by Carroll, Slacalek, Tokuoka, and White (2017)
 - ▶ “Sticky Expectations and Consumption Dynamics” by Carroll, Crawley, Slacalek, Tokuoka, and White (2018)
 - ▶ Several others are close
- ▶ Much room for improvement: endogenous labor supply (e.g.)

Other Consumption-Saving Models in HARK

- ▶ TractableBufferStock: Highly specialized idiosync shocks
- ▶ MarkovModel: $\mathcal{D}, \Gamma, F_\theta, F_\psi, R$ vary by discrete state
- ▶ ExplicitPermInc: Same as IndShock, but not normalized
- ▶ PersistentShock: “Permanent” shocks not fully permanent
- ▶ MedShock: 2nd cons good with random marginal utility
- ▶ MedHealthShock:* Medical shocks plus discrete health states
- ▶ DynInsSel:* ...plus choice over medical insurance contracts

And even more to come...

Consumption-Saving Model Tree



Topics for Further Discussion

Time is short, but I could talk about...

- ▶ Class inheritance / model recombination [Link](#)
- ▶ “Macroeconomic” framework and models [Link](#)
- ▶ To do: endogenous labor supply models [Link](#)
- ▶ To do: durable goods models [Link](#)
- ▶ To do: various bits, large and small [Link](#)

Topics for Further Discussion

Time is short, but I could talk about...

- ▶ Class inheritance / model recombination [Link](#)
- ▶ “Macroeconomic” framework and models [Link](#)
- ▶ Roadmap [Link](#)

Planned Future of Additions to HARK

1. Endogenous labor supply models [Link](#)
2. Durable goods models [Link](#)
3. Various bits, large and small [Link](#)

The Future of HARK: Incorporating Labor (1/4)

Model of labor supply on intensive margin:

$$u(c, \ell) = ((1 - \ell)^\alpha c)^{1-\rho} / (1 - \rho),$$

$$v_t(b_t, \theta_t) = \max_{c_t, \ell_t} u(c_t, \ell_t) + \beta \mathbb{E}_t [(\psi_{t+1} \Gamma_t)^{1-\rho} v_{t+1}(b_{t+1}, \theta_{t+1})] \quad \text{s.t.}$$

$$y_t = \ell_t \theta_t, \quad \ell_t \in [0, 1],$$

$$a_t = m_t + y_t - c_t, \quad a_t \geq \underline{a},$$

$$b_{t+1} = R / (\Gamma_t \psi_{t+1}) a_t,$$

$$\psi_{t+1} \sim F_{\psi_{t+1}}(\psi), \quad \theta_{t+1} \sim F_{\theta_{t+1}}(\theta), \quad \mathbb{E}[\psi_{t+1}] = 1.$$

The Future of HARK: Incorporating Labor (2/4)

Model of labor supply on extensive margin:

$$u(c, \ell) = c^{1-\rho}/(1-\rho) - \alpha\ell,$$

$$v_t(b_t, \theta_t, \ell_{t-1}) = \max_{c_t, \ell_t} u(c_t, \ell_t) + \beta \mathbb{E}_t [(\psi_{t+1} \Gamma_t)^{1-\rho} v_{t+1}(b_{t+1}, \theta_{t+1}, \ell_t)]$$

$$y_t = \ell_t \theta_t, \quad \ell_t \in \{0, \ell_{t-1}\},$$

$$a_t = m_t + y_t - c_t, \quad a_t \geq \underline{a},$$

$$b_{t+1} = R/(\Gamma_t \psi_{t+1}) a_t,$$

$$\psi_{t+1} \sim F_{\psi_{t+1}}(\psi), \quad \theta_{t+1} \sim F_{\theta_{t+1}}(\theta), \quad \mathbb{E}[\psi_{t+1}] = 1.$$

The Future of HARK: Incorporating Labor (3/4)

Model of endogenous employment search:

$$u(c, s) = ((1 - s)^\alpha c)^{1-\rho} / (1 - \rho),$$

$$v_t(m_t, e_t) = \max_{c_t, s_t} u(c_t, s_t) + \beta \mathbb{E}_t [(\psi_{t+1} \Gamma_t)^{1-\rho} v_{t+1}(m_{t+1}, e_{t+1})] \quad \text{s.t.}$$

$$a_t = m_t - c_t, \quad a_t \geq \underline{a}, \quad s_t \in [0, 1],$$

$$m_{t+1} = R/(\Gamma_t^e \psi_{t+1}) a_t + \theta_t e_{t+1} + \underline{b}(1 - e_{t+1}),$$

$$\text{Prob}(e_{t+1} = 1 | e_t = 0) = s_t, \quad \text{Prob}(e_{t+1} = 0 | e_t = 1) = \mathbb{U},$$

$$\psi_{t+1} \sim F_{\psi_{t+1}}^e(\psi), \quad \theta_{t+1} \sim F_{\theta_{t+1}}(\theta), \quad \mathbb{E}[\psi_t] = 1.$$

The Future of HARK: Incorporating Labor (4/4)

Applications of Market for labor models:

- ▶ Non-trivial calculation of $L_t = \int_0^1 \ell_{it} p_{it} \theta_{it} di$ for Cobb-Douglas
- ▶ Disutility of employment search and probability of job loss depend on labor market slackness
- ▶ Can look at behavior in response to change in SS, etc

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The Future of HARK: Durable Goods (1/3)

General durable goods model:

$$u(c, d) = (c^\alpha, d^{1-\alpha})^{1-\rho} / (1 - \rho).$$

$$v_t(m_t, d_t) = \max_{c_t, i_t} u(c_t, d_t) + \beta \mathbb{E}_t [(\psi_{t+1} \Gamma_t)^{1-\rho} v_{t+1}(m_{t+1}, d_{t+1})] \quad \text{s.t.}$$

$$a_t = m_t - c_t, \quad a_t \geq \underline{a},$$

$$D_t = d_t + g(i_t), \quad d_{t+1} = (1 - \delta_{t+1})D_t, \quad \delta_{t+1} \sim F_\delta(\delta),$$

$$m_{t+1} = R / (\Gamma_t \psi_{t+1}) a_t + \theta_{t+1},$$

$$\psi_{t+1} \sim F_{\psi_{t+1}}(\psi), \quad \theta_{t+1} \sim F_{\theta_{t+1}}(\theta), \quad \mathbb{E}[\psi_t] = 1.$$

The Future of HARK: Durable Goods (2/3)

Variations of durable goods model require different solvers:

- ▶ Easiest case: $g(i_t)$ is concave, $i_t \in \mathbb{R}$. Every end-of-period state (a_t, D_t) associated with *some* beginning of period state.
- ▶ Slightly harder: $i_t \geq 0$, must handle constraint
- ▶ Somewhat harder: $g(i_t) = \pi i_t$. One locus in (a_t, D_t) space is optimal; each point on optimal (a_t, D_t) locus associated with locus in (m_t, d_t) space.
- ▶ Even harder: $g(i_t) = \hat{g}(i_t) + K\mathbf{1}(i_t \neq 0)$, with $\hat{g}(0) = 0$ and $\hat{g}(\cdot)$ concave. Must check $i_t = 0$ soln everywhere, discontinuity.
- ▶ Just ugly: $g(i_t) = \pi i_t + K\mathbf{1}(i_t \neq 0)$, $i_t \geq 0$.

The Future of HARK: Durable Goods (3/3)

Applications for Market with durable goods:

- ▶ Endogenous pricing of durable good: housing market
- ▶ Dynamics of demand for durables after an aggregate shock
- ▶ Some specifications overlap with health models

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The Future of HARK: Small To-Do Items

Contributions that would get your feet wet in HARK:

- ▶ Extend perfect foresight to handle borrowing constraint
- ▶ Bequest motives: warm glow, other?
- ▶ Fix/improve aggregate shocks model: handle life cycle models
- ▶ Fix/generalize `ExplicitPermInc` models: `PermGroFunc`
- ▶ Portfolio allocation models; eventually: asset pricing
- ▶ Advanced features on more solvers: cubic spline interpolation
- ▶ Various numeric methods detached from particular models

The Future of HARK: Heavy Lifting

If you're feeling ambitious or are comfortable with HARK:

- ▶ Incorporate `opencl4py` with basic consumption-saving model. “Repack” model inputs into memory buffers, pass to OpenCL solver. OpenCL simulator: easier, big gains for some models.
- ▶ Aggregate shocks with explicit permanent income. One endogenous state variable, two exogenous state variables. Future candidate for GPU computing.
- ▶ Generalized Markov solver: make “solution schema” so that Markov state can be added to any correctly specified solver
- ▶ Models of firm creation / bankruptcy / investment / hiring

Example Model: Basic Consumption-Saving

Consumption-saving model with idiosyncratic permanent and transitory shocks to income (normalized format):

$$u(c) = c^{1-\rho}/(1-\rho).$$

$$v_t(m_t) = \max_{c_t} u(c_t) + \beta \mathbb{E}_t [(\psi_{t+1} \Gamma_{t+1})^{1-\rho} v_{t+1}(m_{t+1})] \quad \text{s.t.}$$

$$a_t = m_t - c_t, \quad a_t \geq \underline{a},$$

$$m_{t+1} = R/(\Gamma_{t+1} \psi_{t+1}) a_t + \theta_{t+1},$$

$$\psi_{t+1} \sim F_{\psi_{t+1}}(\psi), \quad \theta_{t+1} \sim F_{\theta_{t+1}}(\theta), \quad \mathbb{E}[\psi_t] = 1.$$

Example Model: Basic Consumption-Saving

Model solution in two lines:

$$\text{FOC: } u'(c_t) = R\beta \mathbb{E}_t [(\psi_{t+1}\Gamma_{t+1})^{-\rho} v'_{t+1}(m_{t+1})] ,$$

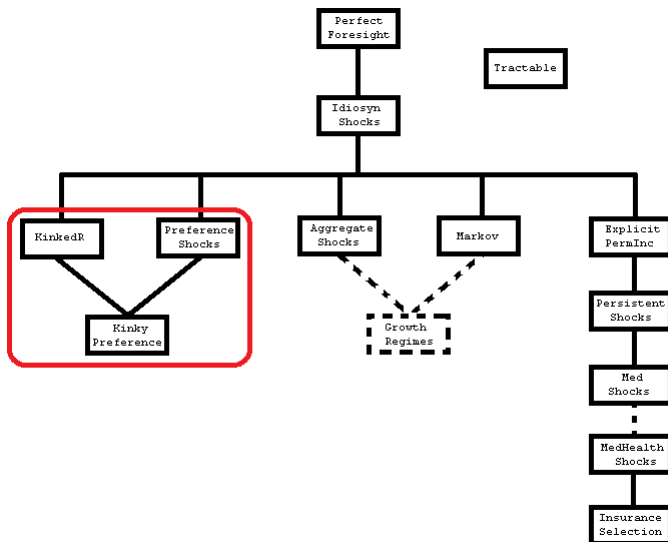
$$\text{EC: } v'_t(m_t) = u'(c_t).$$

Will use endogenous grid method:

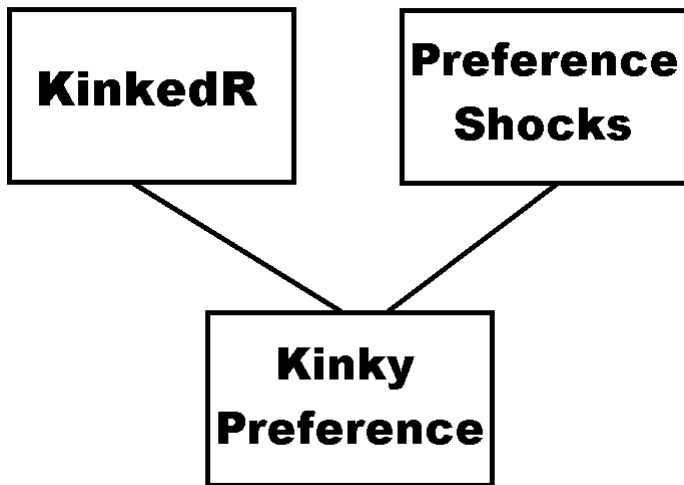
$$v'_t(a_t) \equiv R\beta \mathbb{E}_t [(\psi_{t+1}\Gamma_{t+1})^{-\rho} v'_{t+1}(m_{t+1})|a_t] ,$$

$$c_t = v'_t(a_t)^{-\rho}, \quad m_t = a_t + c_t \text{ (for exogenous set of } \{a_t\} \text{)}.$$

Consumption-Saving Model Tree



Consumption-Saving Model Tree



Kinked R: Costly Borrowing (1/3)

Make one small adjustment to idiosyncratic income shocks model:
interest rate on borrowing is higher than rate on saving.

$$\begin{aligned}u(c) &= \frac{c^{1-\rho}}{1-\rho}, \\v(m_t) &= \max_{c_t} u(c_t) + \beta \mathbb{E}_{t+1} [v_{t+1}(m_{t+1})], \\a_t &= m_t - c_t, \quad a_t \geq \underline{a}, \\m_{t+1} &= R/(\Gamma_{t+1}\psi_{t+1})a_t + \theta_{t+1}, \\\theta_{t+1} &\sim F_{\theta_{t+1}}, \quad \psi_{t+1} \sim F_{\psi_{t+1}}, \quad \mathbb{E}[\psi_{t+1}] = 1, \\R &= \begin{cases} R_{\text{boro}} & \text{if } a_t < 0 \\ R_{\text{save}} & \text{if } a_t > 0 \end{cases}, \quad R_{\text{boro}} \geq R_{\text{save}}.\end{aligned}$$

Kinked R: Costly Borrowing (2/3)

ConsKinkedRsolver inherits from ConsIndShockSolver

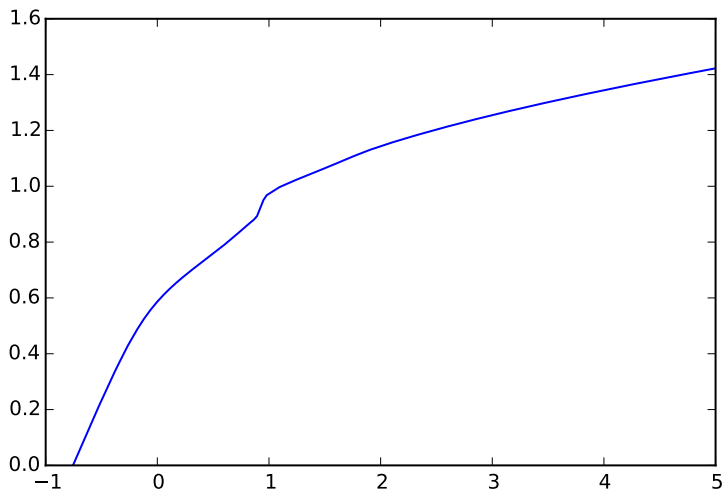
Additions to `__init__` method:

- ▶ Store new attributes `Rboro` and `Rsave`

Additions to `prepareToCalcEndOfPrdvP`:

- ▶ Four lines to use correct value of R for each value of a_t
- ▶ One line to apply that change to calculation of m_{t+1}
- ▶ Three lines to recalculate minimum MPC and human wealth

Kinked R: Costly Borrowing (3/3)



Marginal Utility Shocks (1/4)

Consider another small modification to IndShockModel:

- ▶ Multiplicative (idiosyncratic) shocks to utility each period.
- ▶ Consumption “more valuable” in some periods than others.

$$\begin{aligned}u(c; \eta) &= \eta \frac{c^{1-\rho}}{1-\rho}, & \eta_t &\sim F_\eta, \\v(m_t, \eta_t) &= \max_{c_t} u(c_t; \eta_t) + \beta \mathbb{E}_{t+1} [v_{t+1}(m_{t+1})], \\a_t &= m_t - c_t, & a_t &\geq \underline{a}, \\m_{t+1} &= R/(\Gamma_{t+1}\psi_{t+1})a_t + \theta_{t+1}, \\ \theta_{t+1} &\sim F_{\theta_{t+1}}, & \psi_{t+1} &\sim F_{\psi_{t+1}}, \quad \mathbb{E}[\psi_{t+1}] = 1.\end{aligned}$$

Marginal Utility Shocks (2/4)

New input PrefShkDstn is constructed:

- ▶ PrefShkStd: Standard deviation of (log) pref shocks
- ▶ PrefShkCount: Number of discrete shocks in “body”
- ▶ PrefShkTailCount: Discrete shocks in “augmented tail”

Marginal Utility Shocks (3/4)

ConsPrefShockSolver inherits from ConsIndShockSolver

Additions to `__init__` method:

- ▶ 2 lines: Store preference shock distribution `PrefShkDstn`

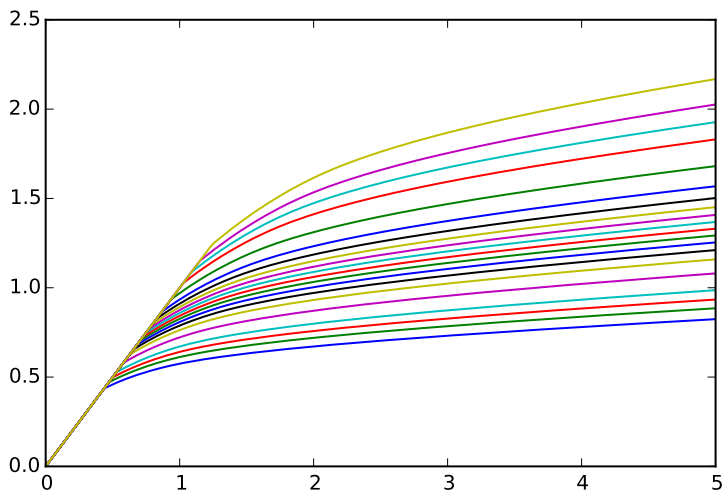
Replace `getPointsForInterpolation`

- ▶ 8 lines: Values of c_t and m_t for each η_t in `PrefShkDstn`

Replace `usePointsForInterpolation`

- ▶ 6 lines: Construct `cFunc` as a `LinearInterpOnInterp1D`
- ▶ 6 lines: Make `vPfunc` by integrating marginal utility across η_t

Marginal Utility Shocks (4/4)



Combination Inheritance: “Kinky Preferences” (1/4)

Combine those two extensions to IndShockModel:

- ▶ Borrowing has higher interest rate than saving...
- ▶ ...and there are shocks to marginal utility
- ▶ HARK makes this pretty easy

Combination Inheritance: “Kinky Preferences” (2/4)

$$\begin{aligned}
 u(c, \eta) &= \eta \frac{c^{1-\rho}}{1-\rho}, & \eta_t &\sim F_\eta, \\
 v(m_t, \eta_t) &= \max_{c_t} u(c_t) + \beta \mathbb{E}[v_{t+1}(m_{t+1})], \\
 a_t &= m_t - c_t, & a_t &\geq \underline{a}, \\
 m_{t+1} &= R/(\Gamma_{t+1}\psi_{t+1})a_t + \theta_{t+1}, \\
 \theta_{t+1} &\sim F_{\theta_{t+1}}, & \psi_{t+1} &\sim F_{\psi_{t+1}}, \quad \mathbb{E}[\psi_{t+1}] = 1, \\
 R &= \begin{cases} R_{boro} & \text{if } a_t < 0 \\ R_{save} & \text{if } a_t > 0 \end{cases}, & R_{boro} &\geq R_{save}.
 \end{aligned}$$

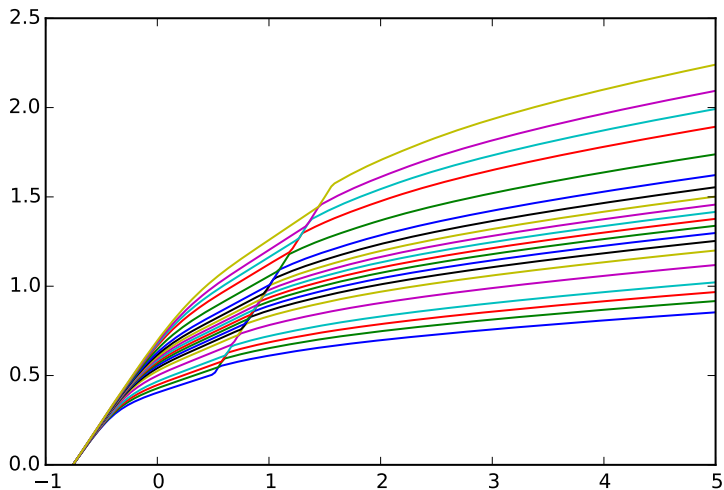
Combination Inheritance: “Kinky Preferences” (3/4)

ConsKinkyPrefSolver inherits from two parent classes. Entirety of the code for the solver:

```
class ConsKinkyPrefSolver(ConsPrefShockSolver,ConsKinkedRsolver):  
    def __init__(self,solution_next,...):  
        ConsKinkedRsolver.__init__(self,solution_next,...)  
        self.PrefShkPrbs = PrefShkDstn[0]  
        self.PrefShkVals = PrefShkDstn[1]
```

Combination Inheritance: “Kinky Preferences” (4/4)

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Macroeconomics in HARK (1/5)

- ▶ Some inputs to micro models are exogenous to each agent...
- ▶ ...But endogenous to collective whole of agents
- ▶ Might be static quantities or dynamic processes
- ▶ Equilibrium: consistency between what agents *believe* the endogenous objects are and what values / dynamic processes *actually occur* when agents act on those beliefs
- ▶ Fixed point in the space of beliefs
- ▶ Need a representation of beliefs about endogenous objects
- ▶ And a rule for how agents form beliefs from observing history

Macroeconomics in HARK (2/5)

“The computational algorithm has two key features. First, it is based on bounded rationality in the sense that we endow agents with boundedly rational perceptions of how the aggregate state evolves... Second, we use solution by simulation, which works as follows: (i) given the boundedly rational perceptions, we solve the individuals' problems using standard dynamic programming methods; (ii) we draw individual and aggregate shocks over time for a large number of individuals; (iii) ...we generate a time series for all aggregates; and finally (iv) we compare the perceptions about the aggregates to those in the actual simulations, and these perceptions are then updated. We think this approach... can be productive for other applications.”

–Per Krusell and Tony Smith (2006)

Macroeconomics in HARK (3/5)

HARK operationalizes K-S method with a farming metaphor:

1. Solve agents' microeconomic problem for some beliefs
2. Simulate many agents for many periods by looping on:
 - ▶ sow: Distribute current aggregate variables to agents
 - ▶ cultivate: Agents act according to their micro solution
 - ▶ reap: Collect some individual variables from the agents
 - ▶ mill: Generate aggregate variables from individual vars
 - ▶ store: Record some information in a "history"
3. Use history to update beliefs about endogenous objects

Market's method solve loops on this process until convergence.

Macroeconomics in HARK (4/5)

Attributes of a Market instance (or subclass):

- ▶ `agents`: List of `AgentType` instances in market
- ▶ `dyn_vars`: Names of the endogenous objects
- ▶ `sow_vars`: Names of aggregate variables
- ▶ `reap_vars`: Individual variables that form aggregates
- ▶ `track_vars`: Aggregates that need to be recorded in history
- ▶ `millRule`: Function that transforms `ind` \rightarrow `agg` variables
- ▶ `calcDynamics`: Function that transforms history into beliefs

Macroeconomics in HARK (5/5)

Extra methods of a Market-compatible AgentType:

- ▶ `marketAction`: What agents *do* to generate `reap_vars`.
Often just simulate one period with `simOnePeriod`
- ▶ `reset`: How to initialize for a new history: reset states

Trivial to add more *ex ante* heterogeneity: just add more AgentType instances to agents!

Consumption-Saving with Aggregate Productivity Shocks

$$v_t(m_t, M_t) = \max_{c_t} u(c_t) + \beta \mathbb{E}_{t+1} [v_{t+1}(m_{t+1}, M_{t+1})],$$

$$a_t = m_t - c_t, \quad a_t \geq 0,$$

$$m_{t+1} = \frac{R_{t+1} a_t}{\Gamma_{t+1} \psi_{t+1} \Psi_{t+1}} + W_{t+1} \theta_{t+1} \Theta_{t+1} \ell,$$

$$A_t = \mathbf{A}(M_t), \quad k_{t+1} = (1 - \delta) A_t / (\Psi_{t+1} \ell),$$

$$R_{t+1} = \mathbf{R}(k_{t+1} / \Theta_{t+1}), \quad W_{t+1} = \mathbf{W}(k_{t+1} / \Theta_{t+1}),$$

$$M_{t+1} = R_{t+1} k_{t+1} + W_{t+1} \Theta_{t+1} \ell$$

$$\theta_{t+1} \sim F_{\theta_{t+1}}, \quad \psi_{t+1} \sim F_{\psi_{t+1}}, \quad \mathbb{E}[\psi_{t+1}] = 1,$$

$$\Theta_{t+1} \sim F_{\Theta}, \quad \Psi_{t+1} \sim F_{\Psi}, \quad \mathbb{E}[\Psi_{t+1}] = \mathbb{E}[\Theta_{t+1}] = 1.$$

Consumption-Saving with Aggregate Productivity Shocks

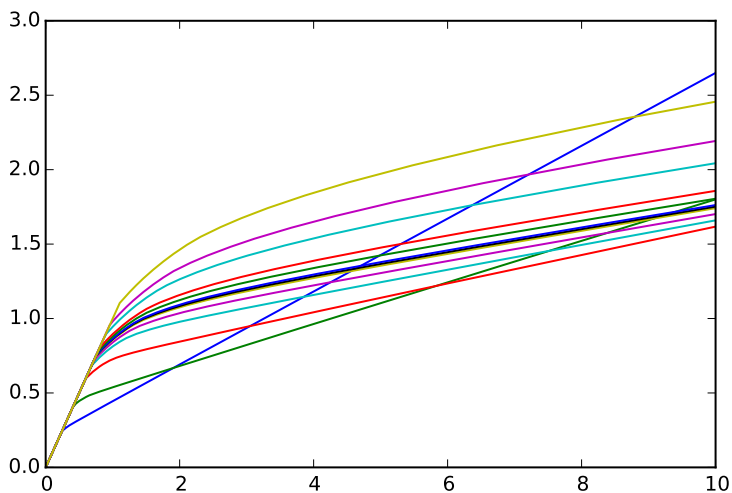
Some totally new inputs for an `AggShockConsumerType`:

- ▶ `Rfunc` and `wFunc`: Factor payments as function of k_t
- ▶ `Mgrid`: Grid of M_t state values (sort of constructed)
- ▶ `Afunc`: $\mathbb{E}[A_t|M_t] = \mathbf{A}(M_t)$

`IncomeDstn` combines idiosyncratic and aggregate shocks:

- ▶ Discrete approximation to aggregate shock distribution constructed like idiosyncratic shocks: `PermShkAggStd`, `TranShkAggStd`, `PermShkAggCount`, `TranShkAggCount`
- ▶ `IncomeDstn` has five elements: probs, idio shocks, agg shocks

Consumption-Saving with Aggregate Productivity Shocks



Cobb-Douglas Economy in the Market Framework

CobbDouglasEconomy is a subclass of Market:

- ▶ sow: Distribute $(M_t, R_t, W_t, \Theta_t, \Psi_t)$ to consumers
- ▶ cultivate: Consumers draw (θ_t, ψ_t) , choose c_t
- ▶ reap: Collect assets a_t and productivity P_t from consumers
- ▶ mill: Calc A_{t+1} , draw $(\Theta_{t+1}, \Psi_{t+1})$, calc k_{t+1}, M_{t+1} , get (R_{t+1}, W_{t+1})
- ▶ store: Record M_t and A_t in their histories

Loop that process for (say) 1000 periods

- ▶ calcDynamics: Regress $\log(A_t)$ on $\log(M_t)$, make new **A**
- ▶ Distribute new **A** to consumers as Afunc

Other Applications of Market

Krusell and Smith were right: method is applicable to other topics

- ▶ Premiums of medical insurance contracts: actuarial constraint maps *who* buys each contract to break even premium, subject to informational constraints (sex, age, health, etc)
- ▶ Papageorge et al risky sex framework: probability of contracting HIV from risky sex act depends on HIV infection rate and risky sex choices of the population
- ▶ Agent-to-agent interaction: could sow a permutation of what is reaped: imperfect knowledge, contagion of information, moves closer to “agent-based modeling”

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