ECON408: Computational Methods in Macroeconomics

Asset Pricing, Lucas Trees, and Options

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Overview

Motivation

- We have used asset pricing examples as practice in dynamic programming and EPDVs, but have not explored the economics of these models
- In the Permanent Income Model lectures we analyzed the role of intertemporal smoothing and risk-aversion in helping consumers smooth consumption.
- Here, rather than considering an exogenous interest rate we will consider where asset prices should come from in a general equilibrium model
  - → We will follow a variation of Lucas (1978) and build connections to Harrison and Kreps (1979) and Hansen and Richard (1987)

Materials

- Adapted from QuantEcon lectures coauthored with John Stachurski and Thomas J. Sargent
  - → Asset Pricing I: Finite State Models
  - → Asset Pricing II: The Lucas Asset Pricing Model

```julia
using LinearAlgebra, Statistics
using Distributions, LaTeXStrings, QuantEcon
using Plots.PlotMeasures, NLsolve, Roots, Random, Plots
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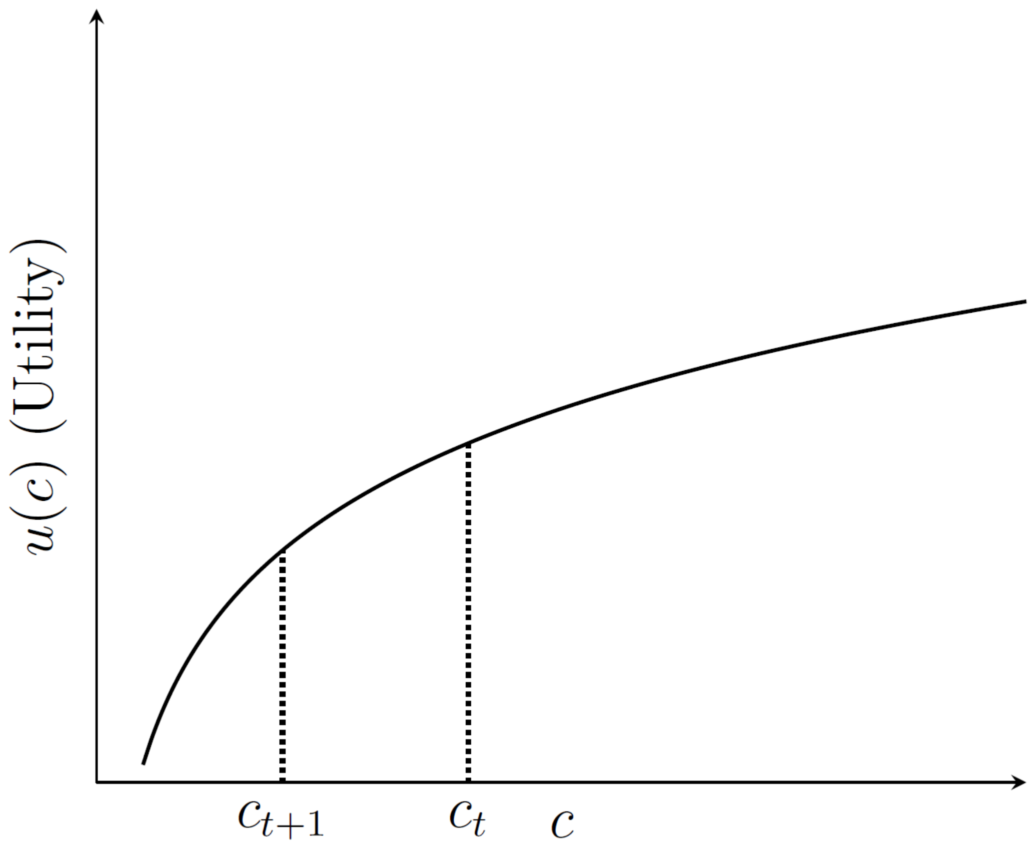
Review of Preferences

Period Utility

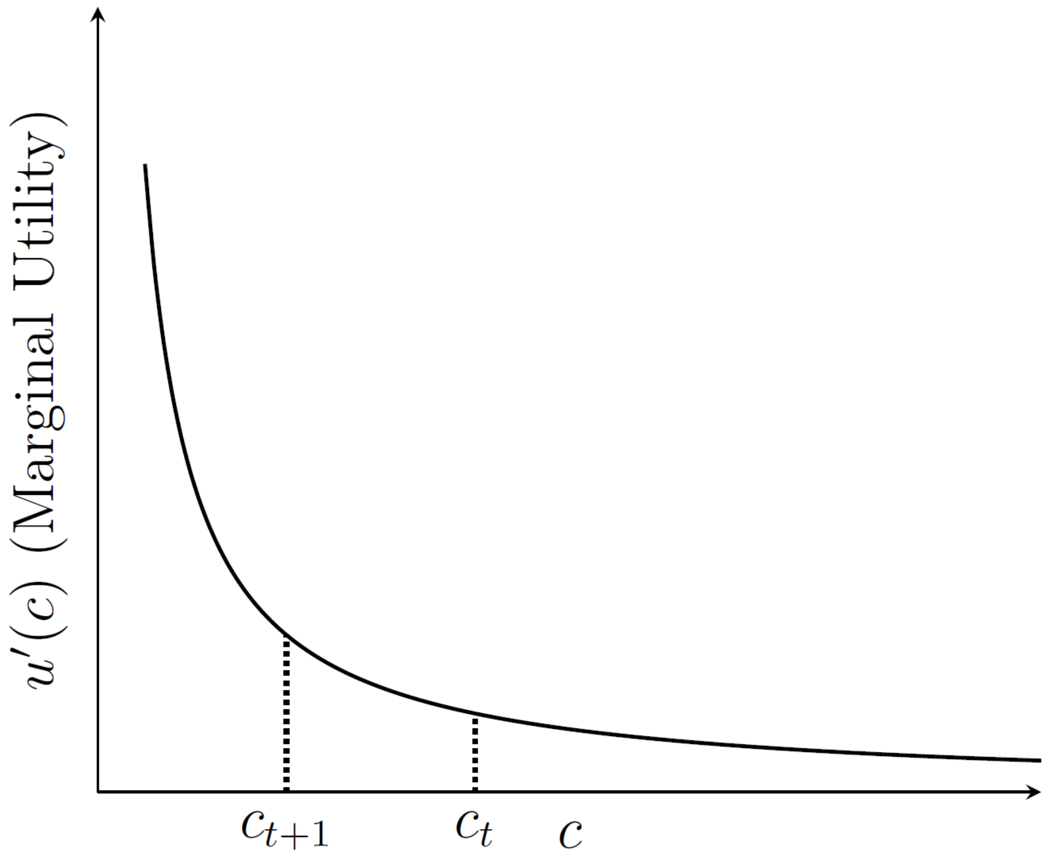
- **Notation warning:** will occasionally use derivatives, such as the utility $u'(c)$ we mean derivative, but in other cases we will use write the problem recursively and reserve c' for the next period notation
  - → Confusing at first, but you will see it used often in macroeconomics
- Consider utility which is strictly concave where:
  - → $u'(c) > 0$: More is better
  - → $u''(c) \leq 0$: (Weakly) Diminishing Marginal Utility
- Examples include
  - → $u(c) = \log(c)$ and $u(c) = \frac{c^{1-\gamma}}{1-\gamma}$ for $\gamma > 0$
  - → If $u''(c) = 0$ then we have a linear utility function, $u(c) \propto c$ and $u'(c)$ is constant

Strictly Concave Utility



- Positive Marginal Utility of Consumption
- Diminishing Returns
- No (visible, at least) point of satiation

Marginal Utility



- $u'(c) > 0$ but decreasing $u''(c) < 0$
- $u'(c_1) = u'(c_2) \implies c_1 = c_2$
- If $u'(c_t) < u'(c_{t+1})$ then $c_t > c_{t+1}$
- The less they consume, the more valuable additional consumption in that period would be

Uncertainty

- What if the agent does not know $\{c_t\}_{t=0}^{\infty}$ because it is random or uncertain?
- In that case, we can instead have the agent compare expected utility streams

$$\mathbb{E}_t \left[\sum_{j=0}^{\infty} \beta^j u(c_{t+j}) \right]$$

→ Where $\mathbb{E}_t[\cdot] \equiv \mathbb{E}[\cdot|I_t]$ with I_t the information set we make available at time t for forecasting in our model

→ This uses our model of expectation formation from the previous lecture

Risk Aversion vs. Inter-temporal Substitution

- If $u(c)$ is strictly concave the agent:
  - → **Risk Averse:** Prefers more deterministic consumption to those with a higher variance
  - → **Preferences for Consumption Smoothing:** Will substitute between time periods rather than smoother consumption over time rather than large fluctuations
- One challenge in macroeconomics with these preferences is that the $u(c)$ serves both purposes, which have different economic interpretations.
  - → To disentangle, can use recursive preferences such as Epstein-Zin which decouple these two concepts

Smoothing Incentives

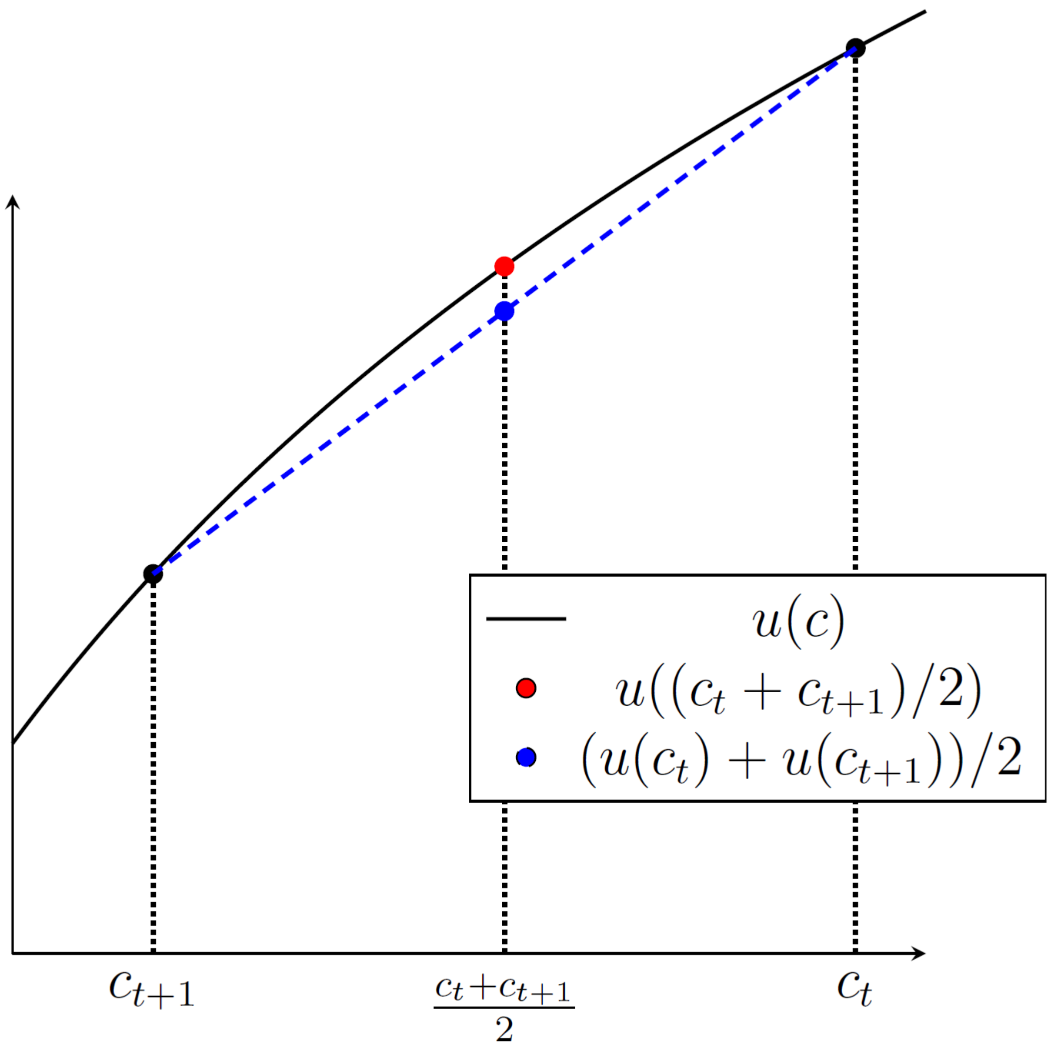
- Consider a simpler case where they live for two periods and don't discount the future: $V(c_1, c_2) \equiv u(c_1) + u(c_2)$
- Consider two possible bundles: $\{c_t, c_{t+1}\}$ and $\{\bar{c}, \bar{c}\}$ where $c_t + c_{t+1} = 2\bar{c}$
- If the agent is risk-neutral, we see that $V(c_t, c_{t+1}) = V(\bar{c}, \bar{c})$
- However, if the agent if risk-averse, then

$$V(c_t, c_{t+1}) < V(\bar{c}, \bar{c}) \quad \textbf{unless } c_t = c_{t+1} = \bar{c}$$

→ They strictly prefer smoother consumption over time

→ i.e., would forgo consumption on average to gain smoother consumption

Smoothing and Concavity



- Recall $\bar{c} \equiv (c_t + c_{t+1})/2$
- 2 periods, $\beta = 1$
- Same "price" for c_t and c_{t+1}
- Two possible bundles:
  1. $\{c_t, c_{t+1}\}$
  2. $\{\bar{c}, \bar{c}\}$
- Later, β and prices will simply distort this exact tradeoff

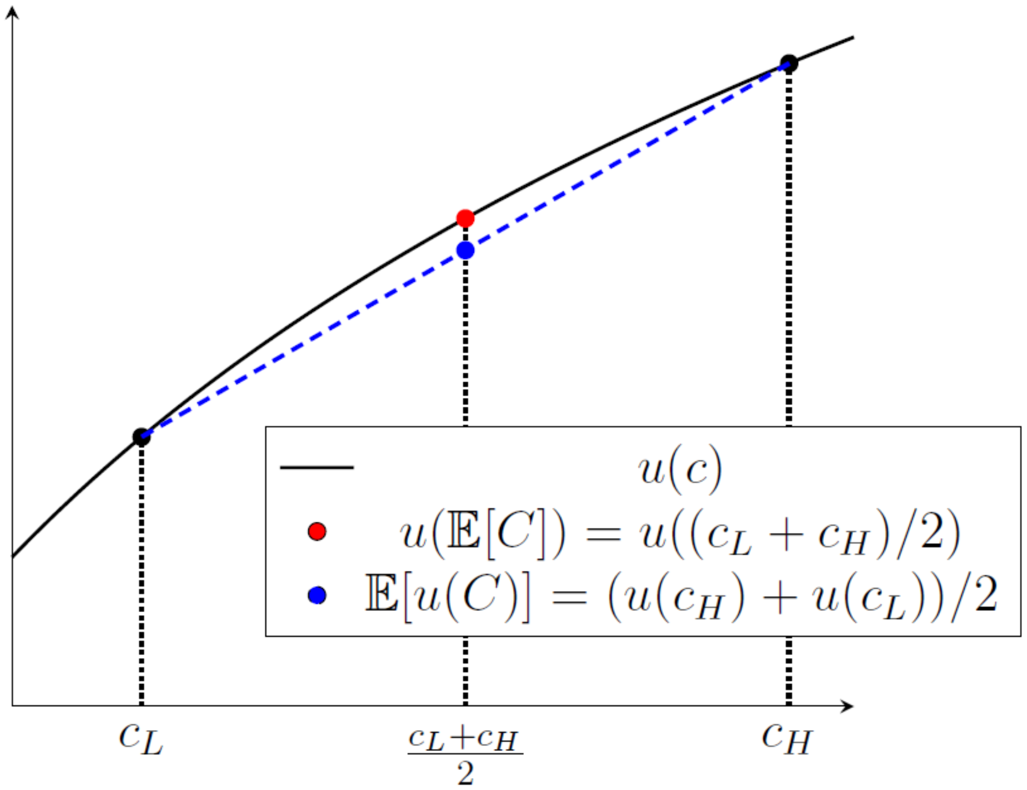
Risk-Aversion Intuition

- Consider a utility $u(c)$ and a lottery which is a random variable
  - → $C = \begin{cases} c_L & \textbf{with probability } \frac{1}{2} \\ c_H & \textbf{with probability } \frac{1}{2} \end{cases}$
  - → Let $(c_L + c_H)/2 = \bar{c}$
  - → We can form expected utility as $\mathbb{E}[u(C)] = \frac{1}{2}u(c_L) + \frac{1}{2}u(c_H)$
- Note if risk-neutral then $\mathbb{E}[C] = \frac{1}{2}c_L + \frac{1}{2}c_H = \bar{c} = u(\bar{c})$
- Then if an agent is risk-averse,

$$u(\mathbb{E}(C)) > \mathbb{E}[u(C)]$$

  - → i.e., would forgo consumption on average to avoid the risk

Risk Aversion and Concavity



- Interpretation as fair, risk-neutral prices for lotteries
- Then compare choice between lotteries:
  1. $\mathbb{E}[u(C)] \equiv \frac{1}{2}u(c_L) + \frac{1}{2}u(c_2)$
  2. $u(\mathbb{E}(C)) = u(\frac{1}{2}c_L + \frac{1}{2}c_H)$
- The strict concavity of $u(c)$ shows you are better off with the deterministic consumption

Consumption Based Asset Pricing

Why Study This Problem?

- Macro-finance and financial economics $\neq$ pure finance. Different goals and questions, though sometimes common tools
- If you are interested in macro-finance, then this is the core theory of aggregate asset prices (“consumption-based asset pricing”)
- Even if you do not care about macro-finance or financial economics, macroeconomists need to understand asset prices because they are tightly connected to models of saving and investment
- Finally, if you have a model of asset pricing you can use it to invert consumer expectations of the economy from empirical asset prices
  - → e.g., the yield cure (i.e., prices bonds of different maturity) can be used to infer the market’s expectations of future GDP growth

General Equilibrium for Asset Markets

- General Equilibrium (GE) refers to a model where all markets clear simultaneously. Supply equals demand, which determines the price
- The simplest models of asset pricing should have prices such as that of bonds, equities, insurance contracts, etc. determined by the same forces
- Agents might want to purchase assets in order to
  - → Delivery in the future where they expect to want more consumption relative to today (i.e. $u'(c_{t+j}) > u'(c_t)$ after discounting by β^j, etc.)
  - → Delivery in states of the world to hedge against bad outcomes. For example, if they think there is a 50% chance of a bad outcome, they might want to purchase an asset that pays off in that state to smooth consumption - even if it may decrease their average consumption today

Exchange Economies

- The simplest models to understand asset prices are when the "endowments" are exogenous (i.e., the amount of goods each agent cannot be changed by their behavior)
- Then, there may be gains from trade if different agents get their endowments in different states of the world or at different times.
  - → e.g., the young may have more endowments relative to the retired
  - → e.g., employed have endowments at different times than unemployed
- If agents are able to trade these exogenous endowments we call it a "pure exchange economy"

Representative Consumers

- Since we will be looking at prices emerging from supply and demand, it is important to be clear when agents are competitive vs. can exert market power
- We will assume that no individuals have large enough endowments relative to each other that they can unilaterally affect prices of traded assets
- It turns out that if we assume agents have identical preferences and there are complete markets for smoothing consumption, we can solve the model with a single **representative agent** to get the same (aggregate) results
  - → The "endowments" of the representative agent are the sum of the endowments of all agents, i.e. the aggregate endowments
  - → Using a representative agent is an **aggregation result** given particular assumptions on primitives, not an assumption itself

Supply of Goods

- In the simplest version, think of there being a “tree” which produces a random stream of fruit each period.
  - → We are using “fruit” instead of dollars because it is important to consider that this is a physical good, not just a nominal value
- The random sequence of consumption goods (fruit) is $\{d_t\}_{t=0}^{\infty}$
- Let the process determining the fruit be Markov, where for some w_{t+1} iid

$$d_{t+1} = h(d_t, w_{t+1})$$

  - → Since Markov, could also write $d' = h(d, w)$ for IID w
- Assume the “fruit” is **not storable**

Preferences

- At time t the consumer has preferences

$$\mathbb{E}_t\left[\sum_{j=0}^{\infty}\beta^j u(c_{t+j})\right]$$

→ For now, assume that $u(\cdot)$ is strictly concave, but we will consider cases where it is not in the limit (e.g., $\lim_{\gamma\to 0}\frac{c^{1-\gamma}}{1-\gamma}=c$)

- We will solve a competitive equilibrium were the consumer buys and sells claims to the fruit of the tree (i.e., assets) to smooth consumption

Prices and Claims

- Let p_t = price of a claim to the fruit of the tree at time t giving the right to
  - → Claim a unit share of the fruit that falls at time t
  - → Sell that claim in time t or $t+1$, where the (equilibrium) price will be forecast at p_{t+1} given time t information
- If d_t is varying this is "equity" rather than a bond, because there is no guarantee of how many pieces of fruit will fall at that time
- Let the state variable of the firm be π_t which is the number of claims to the fruit of the tree they own at time t

Budget Constraint

- Normalize the price of fruit to 1 at each time period, so p_t is in real terms
  - → Think of this as spot markets for the fruit which we use as a price level
- The consumer has π_t claims to the tree, which delivers $\pi_t d_t$ pieces of fruit
  - → They can sell the fruit for $\pi_t d_t \times 1$
  - → They can sell the claim itself for $p_t \pi_t$
- They may want to:
  - → Purchase $(c_t - \pi_t d_t)$ additional fruit at price 1
  - → Change the number of future claims by purchasing (or selling) $(\pi_{t+1} - \pi_t)$ claims at price p_t
- Putting together, the budget constraint is: $c_t + p_t \pi_{t+1} = \pi_t(d_t + p_t)$

Consumers Problem

- The agent is a **price taker** at p_t (i.e., this is a competitive equilibrium)
- State: π_t and d_t (and information sets for d_{t+j} and p_{t+j} forecasts)
- Taking prices as given, the consumer solves

$$\max_{\{c_{t+j},\pi_{t+j+1}\}_{j=0}^{\infty}} \mathbb{E}_t\left[\sum_{j=0}^{\infty}\beta^j u(c_{t+j})\right]$$
$$\text{s.t. } c_{t+j}+p_{t+j}\pi_{t+j+1}=\pi_{t+j}(d_{t+j}+p_{t+j}),\ \text{for all } j\geq 0$$

  → The first order conditions for this problem will yield a demand function claims to the the fruit tree and the fruit itself

- If d_t is Markov, we can write this problem recursively as a Bellman equation

Dynamic Programming

- Let the Markov price be $p(d)$, then the Bellman equation for the consumer is

$$V(\pi, d) = \max_{c,\pi'} \left[u(c) + \beta \mathbb{E}[V(\pi', d')|d] \right]$$

$$\text{s.t. } c + \pi' p(d) = \pi(d + p(d))$$

  → They forecast d' and $p(d')$ based on their information set

- Substituting the budget constraint into the Bellman equation

$$V(\pi, d) = \max_{\pi'} \left[u(\underbrace{\pi(d + p(d)) - \pi' p(d)}_{c(\pi,\pi',d)}) + \beta \mathbb{E}[V(\pi', d')|d] \right]$$

Euler Equation

- Take the $\partial_{\pi'}$ of the Bellman equation

$$0 = -p(d)u'(\pi(d + p(d)) - \pi' p(d)) + \beta \mathbb{E}[\partial_\pi V(\pi', d')|d]$$

- Next the envelope theorem tells us how the value function changes with respect to the state variable π

$$\partial_\pi V(\pi, d) = u'(c)(d + p(d))$$

- Use $c = \pi(d + p(d)) - \pi' p(d)$, and $d' = h(d, w)$ for $\mathbb{E}[\cdot]$

$$p(d) = \mathbb{E}\left[\beta \frac{u'(c')}{u'(c)}(d' + p(d'))\middle| d\right]$$

Consumption in Equilibrium

- This is the celebrated **consumption-based asset pricing equation**

$$p(d) = \mathbb{E}\left[\underbrace{\beta \frac{u'(c')}{u'(c)}}_{m(c,c')}(d' + p(d'))\middle| d\right]$$

  → Includes properties specific to the asset (e.g., $p(d)$ and d)

  → Includes consumers' preferences and process for consumption. Collect into $m(c, c')$ the **stochastic discount factor**(SDF)

- If the consumer's consumption is tightly connected to the fruit of this particular asset, then there may be a correlation between c and the d and hence between $m(c, c')$ and $d' + p(d')$

Sequential Notation

- In that case, lets directly use the m_{t+1} has a stochastic process
- It could have any correlation with a particular d_{t+1} process
  - → In fact, maybe being negatively correlated is a good thing for smoothing risks?
- In that notation, the asset pricing equation is

$$p_t = \mathbb{E}_t \left[m_{t+1}(d_{t+1} + p_{t+1})\right]$$

  - → However, this is just notation and we can switch for convenience
- Note that the first payoff of the “dividend” occurs at $t+1$. This is called **ex-dividend** pricing

Reminder: Permanent Income Model

- In the permanent income model, the consumer could purchase a 1-period riskless asset which paid 1 with certainty.
  - → Extending so the price of the risk-free asset might change as R_t
- The **Euler Equation**

$$u'(c_t) = \beta R_t \, \mathbb{E}_t[u'(c_{t+1})]$$
$$p_t^{RF} \equiv \frac{1}{R_t} = \mathbb{E}_t\left[\beta \frac{u'(c_{t+1})}{u'(c_t)}\right]$$

  - → Converts gross interest rate R_t to a price on 1 period asset p_t^{RF}

Connecting to the Asset Pricing Formula

- Back to our current setup. Since the risk-free asset has no future claims, $p_{t+1}^{RF} = 0$ and since it is risk-free the $d_{t+1} = 1$

$$
\begin{aligned}
p_t^{RF} &= \mathbb{E}_t\left[m_{t+1}(d_{t+1} + p_{t+1}^{RF})\right] \\
p_t^{RF} &= \mathbb{E}_t\left[m_{t+1}(1 + 0)\right] \\
&= \mathbb{E}_t\left[\beta \frac{u'(c_{t+1})}{u'(c_t)}\right] = \frac{1}{R_t}
\end{aligned}
$$

→ Previously: Given an R_t, find c_t, c_{t+1}

→ Now: Given the c_t, c_{t+1}, could we find the R_t that would reconcile the asset pricing equation with consumer's optimality?

Aggregate Endowment and Complete Markets

Example: Claim to the Aggregate Endowment

- Consider if the tree is the full output of the economy
  - → Interpretation: a claim to real GDP per capita
- In that case, the
  - → demand is determined by the asset pricing equation
  - → supply is inelastic (since it is an endowment)
- Market clearing requires that $c = d$ for all states
- Substitute into the equation to get the price of a claim to the aggregate endowment (e.g., a perfectly diversified equity index)

Asset Pricing Equation

- We can now write down the equation determining the price of a claim to the aggregate endowment

$$p(d) = \mathbb{E}\left[\beta \frac{u'(d')}{u'(d)}(d' + p(d')) \middle| d\right]$$

  → Where the process $d' = h(d, w)$ defines the conditional expectations

- This $p(d)$ is now a recursive equation which we can solve for all d

Interpretation of the SDF for $c = d$

- The "fruit" process (e.g., GDP) effects asset prices through two channels
- First consider how $d' > d$ affects $m(d, d')$
  - → Due to market clearing, more endowment tomorrow relative to today means that the ratio of marginal utilities will be higher
  - → Hence the asset prices will be need to rise to make the consumer indifferent between consuming today and tomorrow (after discounting)
  - → Higher asset prices deter borrowing, which ensures that markets can clear given the fixed endowment today
  - → Otherwise, the consumer would want to borrow against the future (i.e., Permament Income model)

Interpretation of the Dividend and Price Forecasts

- Next, the $d' + p(d')$ term is more mechanical in

$$p(d) = \mathbb{E}\left[\beta \frac{u'(d')}{u'(d)}(d' + p(d'))\middle| d\right]$$

→ If d' is higher (in expectation) then the $p(d)$ will be higher since it is a claim to the future endowment

→ In addition, if there is an any persistence in d then a higher d today will lead to the probability of a higher d' tomorrow, which will also raise the price of the claim to the endowment

- Suggests crucial to understand how m' and d' are correlated

Assets under Complete Markets

- Consider a case with **complete market** where the consumer can purchase financial assets to help smooth consumption against all possible idiosyncratic and aggregate states of the world
  - → In particular, if there income/endowment fluctuates over time, they would trade with people who have the opposite fluctuations
  - → If the income fluctuates idiosyncratically, trade with people in the opposite states
- Consider more broadly than just financial assets
  - → e.g., insurance contracts, implicit contracts with family, government social insurance, etc.
- Can't smooth fluctuations to **aggregate endowment** (e.g., GDP)

Complete Markets and Aggregate Endowment

- In a world with complete markets and identical preferences, you can show that all idiosyncratic preferences will be hedged against, and any individual asset cannot affect the aggregate.
- $m(c, c')$ is the right way to discount for claims to the **aggregate endowment**, which can have its own stochastic process
- But more importantly, given the perfect diversification, the consumer should use that same $m(c, c')$ for all assets!
  → Otherwise, there would be arbitrage opportunities

Conditional Covariances

- For any random variables x_{t+1} and y_{t+1}
- The definition of the conditional covariance $\mathbf{cov}_t(x_{t+1}, y_{t+1})$ is

$$\mathbb{E}_t(x_{t+1}y_{t+1}) \equiv \mathbf{cov}_t(x_{t+1}, y_{t+1}) + \mathbb{E}_t x_{t+1}\mathbb{E}_t y_{t+1}$$

- The key to understanding the price of an asset with payoff process d_{t+1} will be its covariance with the SDF

Covariances and Asset Prices

- Apply this decomposition to the asset pricing equation

$$\begin{aligned} p_t &= \mathbb{E}_t\left[m_{t+1}(d_{t+1} + p_{t+1})\right] \\ &= \mathbb{E}_t m_{t+1} \mathbb{E}_t(d_{t+1} + p_{t+1}) + \mathbf{cov}_t(m_{t+1}, d_{t+1} + p_{t+1}) \end{aligned}$$

- Recall: m_{t+1} measures value of consumption in different states
- For example, if consumption in a state is lower relative to today means $u'(c_{t+1})/u'(c_t)$ is higher and m_{t+1} is higher
  → Then, if d_{t+1} has a positive covariance with m_{t+1}, (i.e., it pays more in states where the SDF is higher) the price of the asset will be higher

  → Asset hedges against bad states

Risk-Free Asset and SDF

- Risk-free asset is a claim to one unit of consumption tomorrow with certainty
- The SDF m_{t+1} is a random variable which says how much you value payoff tomorrow in various states of the world
- Given the complete markets in the economy we see that

$$\frac{1}{R_t^{RF}} = \mathbb{E}_t\left[\beta\frac{u'(c_{t+1})}{u'(c_t)}\right] = \mathbb{E}_t\left[m_{t+1}\right]$$

- Powerful tool: given asset prices such as the interest rate, and a functional form of m_{t+t} you can infer the market expectations of c_{t+1}/c_t

Finite State Asset Pricing

Finite State Markov Processes

- Using our tools from above, lets consider that the m_t and d_t follow a finite state Markov process (i.e., a Markov Chain)
- The processes will have variance degrees of covariance
  - → The extreme example is if $d_t = c_t$ as in the previous example, then the m_t will be perfectly correlated with d_t
  - → A perfect hedge against GDP would be have a perfect negative correlation
- Let the underlying random variable which generates the random states of both m_t and d_t processes be X_t

Growth Rates of “Dividends”

- Given that the growth rates of payoffs (and its correlation to the SDF) will be essential, define the growth rate of the endowments (e.g. dividends) as

$$d_{t+1} = G_{t+1} d_t$$

  → Assume for simplicity that the growth rates are themselves IID

- Since the underlying random variable is X_t we can write this as

$$G_{t+1} = G(X_{t+1})$$

- Similarly, the SDF is IID and may be correlated with G_t through X_t

$$m_{t+1} \equiv m(X_{t+1})$$

Finite States

- Consider if $X_t \in \{x_1, \ldots x_N\}$ a Markov Chain where

$$P_{ij} \equiv \mathbb{P}(X_{t+1} = x_j \,|\, X_t = x_i), \qquad \text{for } i = 1, \ldots N, j = 1, \ldots N$$

- Baseline growth factor: $G(x_i) = \exp(x_i)$, with $x_i > 0$ for all $i = 1, \ldots N$, and hence $\log G(x_i) = x_i$
- Baseline process for X_t: discretized AR(1) process using Tauchen's Method
  - → e.g. $X_{t+1} = \rho X_t + \sigma w_{t+1}$ where the mean of the stationary distribution is $X_\infty = 0$ and hence $G(X_\infty) = 1$. No growth on average
  - → Correlation ρ helpful for interpretation

Price to Dividend Ratio

- Let the price to dividend ratio be $v_t \equiv p_t/d_t$
- Divide the pricing equation by d_t

$$
\begin{aligned}
p_t &= \mathbb{E}_t\left[m_{t+1}(d_{t+1} + p_{t+1})\right] \\
\frac{p_t}{d_t} &= \mathbb{E}_t\left[m_{t+1}\frac{d_{t+1}}{d_t}\left(1 + \frac{p_{t+1}}{d_{t+1}}\right)\right] \\
v_t &= \mathbb{E}_t\left[m_{t+1}G_{t+1}(1 + v_{t+1})\right] \\
v(X_t) &= \mathbb{E}\left[m(X_{t+1})G(X_{t+1})(1 + v(X_{t+1}))\middle| X_t\right]
\end{aligned}
$$

- This lets us describe the price-to-dividend ratio which is scaleless. Similarly, as m_{t+1} is typically a ratio of marginal utilities, it is also scaleless

Price to Dividend Ratio with Markov Chain

- Price to dividend called Price to Earnings (P/E) ratio in equity markets
- Continuing with this example, given the Markov Chain

$$v(X_t) = \mathbb{E}\left[m(X_{t+1})G(X_{t+1})(1 + v(X_{t+1}))\middle|X_t\right]$$

$$v_i = \sum_{j=1}^{N} m(X_j)G(x_j)(1 + v_j)P_{ij}$$

→ We can stack these equations for all $i = 1, \ldots N$ into a vector v

→ Then solve for the v vector - which is a linear equation for any $G(\cdot)$ and $m(\cdot)$

Risk Neutral Examples

Risk-Neutral Asset Pricing

- If risk-neutral, then $m_{t+1} = \beta$ for all X_t
- Given the finite number of states, we can find a vector $v_t = v(X_t)$
- Define the matrix K where $K_{ij} \equiv G(x_j)P_{ij}$ and

$$
\begin{aligned}
v_i &= \beta \sum_{j=1}^{N} K_{ij}(1 + v_j) \quad \text{for } i = 1, \ldots N \\
v &= \beta K(\mathbb{1} + v) \\
v &= (I - \beta K)^{-1} \beta K \mathbb{1}
\end{aligned}
$$

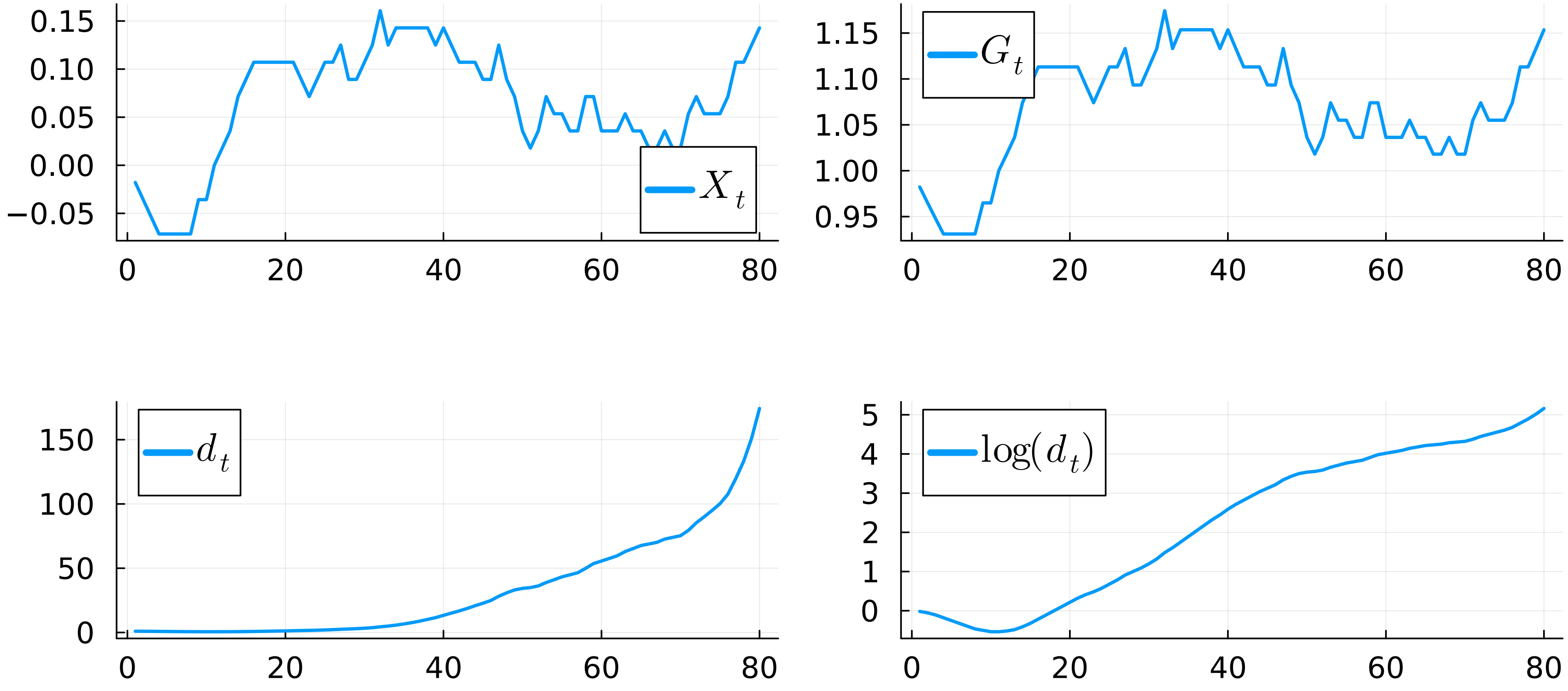
→ Assuming the $\max\{|\text{ eigenvalue of } A|\} < 1/\beta$ as in LSS examples

Risk-Neutral Simulation

```
n = 25
mc = tauchen(n, 0.96, 0.02)
sim_length = 80
X_0_ind = 12
X_t = simulate(mc, sim_length; init = X_0_ind)
G_t = exp.(X_t)
d_0 = 1
d_t = d_0 * cumprod(G_t)

series = [X_t G_t d_t log.(d_t)]
labels = [L"X_t" L"G_t" L"d_t" L"\log(d_t)"]
plot(series; layout = 4, labels)
```

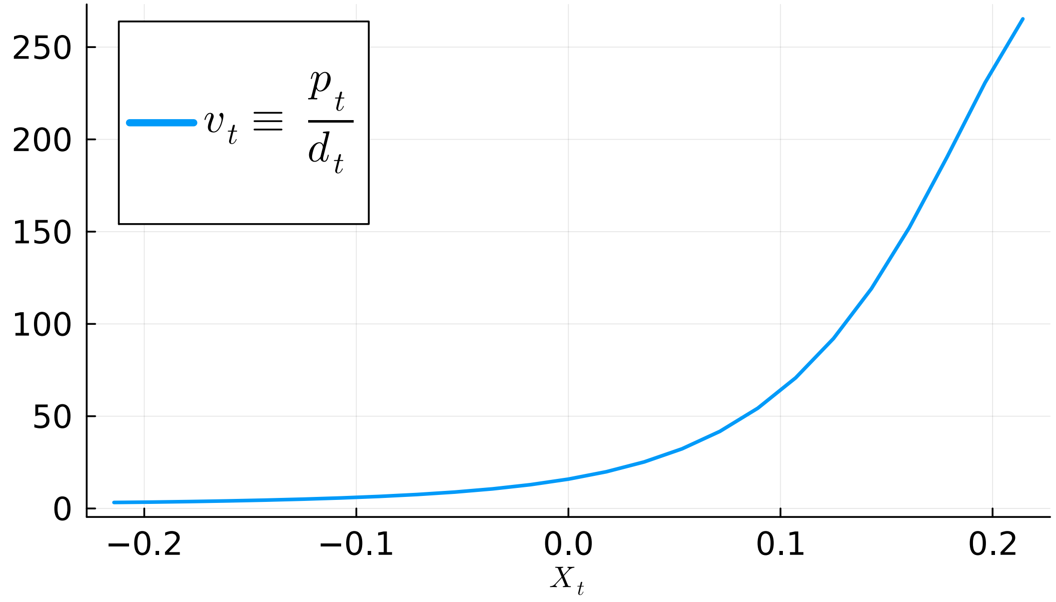
Risk-Neutral Simulation



Price-Dividend Ratios for Risk-Neutral Assets

```julia
beta = 0.9
K = mc.p .* exp.(mc.state_values)'
v = (I - beta * K) \ (beta * K * ones(n, 1))

plot(mc.state_values, v; xlabel = L"X_t",
     label = L"v_t \equiv \frac{p_t}{d_t}",
     size = (600, 400))
```



Interpretation

- Remember that $m_{t+1} = \beta$, so this is not driven by the SDF or the correlation between the SDF and the dividend process
- Why does the price-dividend ratio increase with the state?
  - → The Markov process is positively correlated, so high current states suggest high future states
  - → Moreover, dividend growth is increasing in the state, which is persistent
- Hence, high future dividend growth leads to a high price-dividend ratio

Risk Averse Examples

Pricing with CRRA and Lucas Tree SDF

- Utility: $u(c) = \frac{c^{1-\gamma}-1}{1-\gamma}$ **with** $\gamma > 0$
  - → Then $u'(c) = c^{-\gamma}$, nesting $\log$ utility if $\gamma = 1$
- With complete market, $d_t = c_t$ and the SDF is

$$m_{t+1} = \beta \frac{u'(c_{t+1})}{u'(c_t)} = \beta \left(\frac{c_{t+1}}{c_t} \right)^{-\gamma} = \beta G_{t+1}^{-\gamma}$$

Price-Dividend Ratio for CRRA

- Substitute this into the formula for the price-to-dividend ratio

$$v(X_t) = \beta \mathbb{E}_t \left[G(X_{t+1})^{-\gamma} G(X_{t+1})(1 + v(X_{t+1})) \right]$$
$$v_i = \beta \sum_{j=1}^{N} G(x_j)^{1-\gamma}(1 + v_j)P_{ij}$$

- Rearranging as a fixed point with $J_{ij} \equiv G(x_j)^{1-\gamma} P_{ij}$

$$v = \beta J(\mathbb{1} + v)$$
$$v = (I - \beta J)^{-1} \beta J \mathbb{1}$$

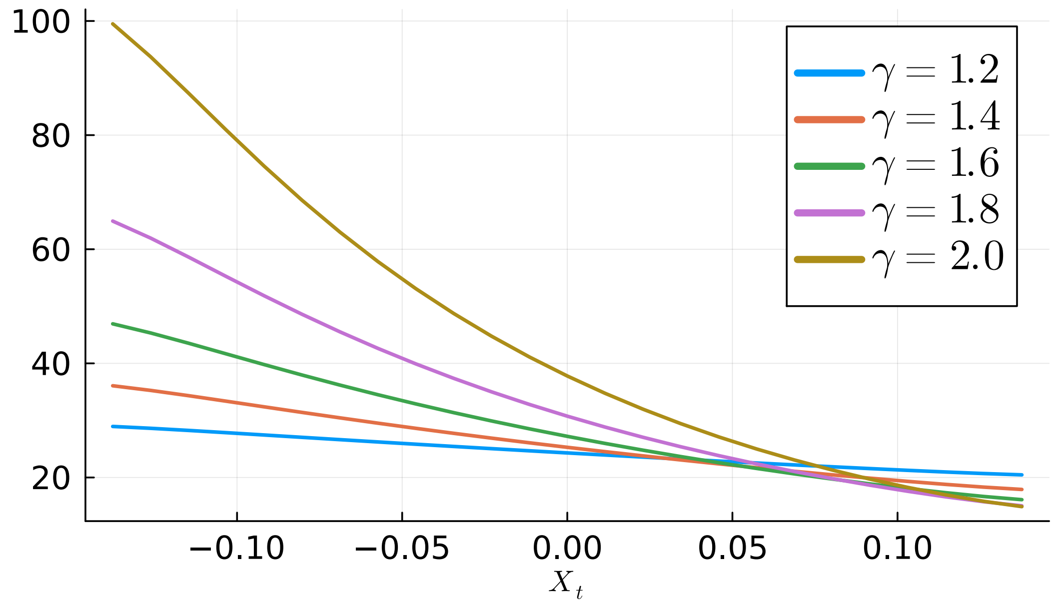
Implementation

```julia
function asset_pricing_model(; beta = 0.96, gamma = 2.0, G = exp,
                               mc = tauchen(25, 0.9, 0.02))
    return (; beta, gamma, mc, G)
end
# price/dividend ratio of the Lucas tree
function tree_price(ap)
    (; beta, mc, gamma, G) = ap
    P = mc.p
    y = mc.state_values'
    J = P .* G.(y) .^ (1 - gamma)
    @assert maximum(abs, eigvals(J)) < 1 / beta # check stability
    v = (I - beta * J) \ sum(beta * J, dims = 2)
    return v
end
```

Price-Dividend for Various Risk-Aversion Parameters

```julia
gammas = [1.2, 1.4, 1.6, 1.8, 2.0]
p = plot(; xlabel = L"X_t", size=(600,400))

for gamma in gammas
    ap = asset_pricing_model(; gamma)
    states = ap.mc.state_values
    plot!(states, tree_price(ap);
          label = L"\gamma = %$gamma")
end
p
```



Interpretation

- Keep in mind that this is with perfectly correlated m_{t+1} and d_{t+1}
- Notice that v is decreasing in each case, in contrast to the risk-neutral case
- This is because, with a positively correlated state process, higher states suggest higher future consumption growth.
- In the stochastic discount factor, higher growth decreases the discount factor, lowering the weight placed on future returns
- Special cases:
  - → If $\gamma = 1$ then the v is constant, as the forces exactly cancel
  - → If $\gamma = 0$ then the v nests the risk-neutral case

A Risk-Free Consol

- A risk-free consol pay a constant amount, a fixed coupon each period forever
- Asset has
  - → ζ in period $t+1$ (i.e., $d_{t+1} = \zeta$)
  - → the right to sell the claim for p_{t+1} next period

$$p_t = \mathbb{E}_t \left[m_{t+1}(\zeta + p_{t+1}) \right]$$

$$p_t = \mathbb{E}_t \left[\beta G_{t+1}^{-\gamma}(\zeta + p_{t+1}) \right]$$

$$p_i = \beta \sum_{j=1}^{N} G(X_j)^{-\gamma}(\zeta + p_j) P_{ij}$$

Linear System

- Letting $M_{ij} \equiv P_{ij} G(X_j)^{-\gamma}$ and rewriting in vector notation yields the solution

$$p = (I - \beta M)^{-1} \beta M \zeta \mathbb{1}$$

Implementation

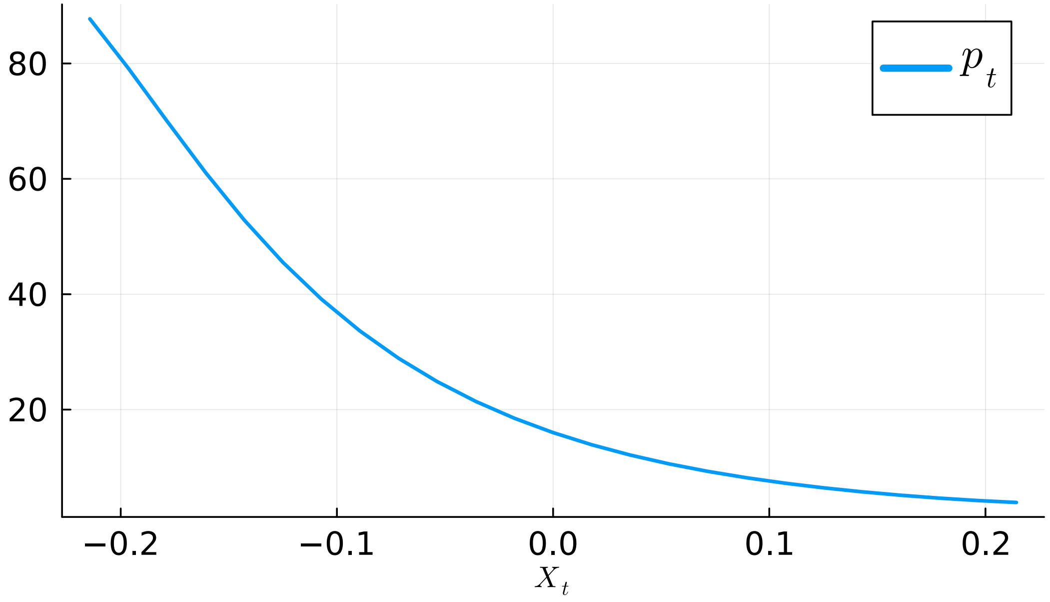
```julia
function consol_price(ap, zeta)
    (; beta, gamma, mc, G) = ap
    P = mc.p
    y = mc.state_values'
    M = P .* G.(y) .^ (-gamma)
    @assert maximum(abs, eigvals(M)) < 1 / beta

    # Compute price
    return (I - beta * M) \ sum(beta * zeta * M, dims = 2)
end
```

Consol Price

```
ap = asset_pricing_model(; beta = 0.9)
zeta = 1.0
strike_price = 40.0

x = ap.mc.state_values
p = consol_price(ap, zeta)
plot(mc.state_values, p; xlabel = L"X_t",
     label = L"p_t",
     size = (600, 400))
```



Option Pricing

Pricing an Option to Purchase the Consol

- An option is a contract that gives the owner the right, but not the obligation, to buy or sell an asset at a specified price
- Many problems in macro are isomorphic to option-pricing problems
  - → e.g.firm entry/exit decisions
- Consider an option to purchase a consol at a price p_S
  - → This will never expire (infinite horizon, or "perpetual" option)
  - → The "call" option gives the owner the right to buy the asset
  - → The price p_S is called the **strike price**
- Let the dynamics of the console be driven by the SDF m_{t+1} and the growth process G_{t+1}

Exercising an Option

- Let $w(X_t, p_S)$ be the value of the option given known X_t but *before* the owner has decided whether or not to exercise the option
  - → Discounts with the SDF $m(X_{t+1})$
- $p(X_t)$ remains the price of the consol itself
- Bellman equation is

$$w(X_t, p_S) = \max\left\{\mathbb{E}_t\left[m(X_{t+1})w(X_{t+1}, p_S)\right],\ p(X_t) - p_S\right\}$$

  - → Left term is value of waiting, right is exercising now.

Option Pricing with Finite State Markov Process

- Using our SDF process

$$w(x_i, p_S) = \max\left\{\beta \sum_{j=1}^{N} P_{ij} G(X_j)^{-\gamma} w(x_j, p_S),\ p(x_i) - p_S\right\}$$

- If we define $M_{ij} \equiv P_{ij} G(X_j)^{-\gamma}$ and stack prices then

$$w = \max\{\beta M w,\ p - p_S \mathbb{1}\}$$

Fixed Point

- To solve this problem, define an operator T mapping vector w into vector $T(w)$ via

$$T(w) = \max\{\beta M w,\ p - p_S \mathbb{1}\}$$

  → To solve this, we can find the fixed point of $T(w) = w$

  → Also a linear complementarity problem in this case

Implementation

```
# price of perpetual call on consol bond
function call_option(ap, zeta, p_s)
    (; beta, gamma, mc, G) = ap
    P = mc.p
    y = mc.state_values'
    M = P .* G.(y) .^ (-gamma)
    @assert maximum(abs, eigvals(M)) < 1 / beta
    p = consol_price(ap, zeta)

    # Operator for fixed point, using consol prices
    T(w) = max.(beta * M * w, p .- p_s)
    sol = fixedpoint(T, zeros(length(y), 1))
    converged(sol) || error("Failed to converge in $(sol.iterations) iter")
    return sol.zero
end
```

Example

```
ap = asset_pricing_model(; beta = 0.9)
zeta = 1.0
strike_price = 40.0

x = ap.mc.state_values
p = consol_price(ap, zeta)
w = call_option(ap, zeta, strike_price)

plot(x, p; xlabel = L"X_t", size=(600,400),
      label = L"p(X_t)")
plot!(x, w; label = L"w(X_t, p_S)")
```