An Algorithm to compute the Stationary Equilibrium in Heterogeneous Agents Models

Lecture 13

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Introduction

- Take a standard problem in quantitative macroeconomics - recursive competitive equilibrium
- Re-write in notation which makes it easy to solve using collocation
  - Based on Miranda and Fackler
  - General notation useful for a lot of problems. Fully vectorized.
  - Type straight into computer
  - Pre-computed integrals (Maliar-Maliar-Judd)
- Robust method for computing stationary distributions
- A simple parallelised bisection method
- Discuss generalisations
- HPC

Simple problem

Agent's problem

The agent takes the price p as given and solves the following given their states (x, z)

$$V(x,z) = \max_{x' \in B(x,z)} F(x,z,x',p) + \beta \sum_{z' \in \mathcal{Z}} P(z,z')V(x',z')$$

Solution $V(x,z)$ and $x'(x,z)$.

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Extensions

- Markov-switching, for example uncertainty regimes
- Discrete choices
- $z' \sim \Gamma(z,z')$, for example $\log(z') = \rho \log(z) + \varepsilon$
- Next period x' subject to iid shock

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Equilibrium

Let $\lambda(x,z)$ be the stationary measure of agents then Λ satisfies

$$\Lambda(x',z') = \int_{X \times Z} \mathbf{1}\left[x'(x,z) \leq x'\right] P(z,z') d\lambda(x,z)$$

Market clearing requires that

$$\bar{x} = \int_{X \times Z} x'(x,z) d\lambda(x,z)$$

Concern for robustness - $\max_{\text{strategy}} \min_{\text{what can go wrong}}$

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- Problem sets
  - Reasonable / already estimated θ, already given p
  - All very well behaved
  - Tend to be solving each piece of a problem separately
  - Ideal Gradient-based solvers for maximization problems, Chebyshev polynomials for approximants.

Concern for robustness - $\max_{\text{strategy}} \min_{\text{what can go wrong}}$

- Problem sets
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  - All very well behaved
  - Tend to be solving each piece of a problem separately
  - Ideal Gradient-based solvers for maximization problems, Chebyshev polynomials for approximants.
- Quantitative work
  - No idea what θ is, always solving for a p
  - Possibly manic
  - All routines are nested
  - Want All routines highly robust. Bisection methods, splines, golden-section search solvers. Tolerances should be highest in the inner-most loop.
  - Want Set-up to be highly flexible. What if I add iid shocks? Uncertainty? Completely different model?

Notation

- Let's call a state $s = (x, z)$

$$V(s) = \max_{x' \in B(s)} F(s, x') + \beta \sum_{z' \in \mathcal{Z}} P(s_2, z') V([x', z'])$$

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- Choose a set of nodes for collocation
- Here focus is on splines, using Chebyshev these are chosen for you.

  See code - Simple way to add curvature to nodes for x

  See code - Way to remove low probability points for z

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  See code - Way to remove low probability points for z
- Result - N_X nodes for x, N_Z nodes for z, matrix $\mathbf{P}$

$$\begin{aligned} \mathbf{s} &= [\mathbf{i}_{N_Z} \otimes \mathbf{x}, \mathbf{z} \otimes \mathbf{i}_{N_X}] \\ N_S &= N_X \times N_Z \end{aligned}$$

Pre-computing integrals - Maliar, Maliar and Judd

- Take the problem and split it in two

$$\mathbf{V}(\mathbf{s}) = \max_{\mathbf{x}' \in \mathbf{B}(\mathbf{s})} \mathbf{F}(\mathbf{s}, \mathbf{x}') + \beta \mathbb{E}\left[\mathbf{V}([\mathbf{x}', \mathbf{z}'])\right]$$

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\mathbf{V}(s) &= \max_{x' \in \mathbf{B}(s)} \mathbf{F}(s, x') + \beta \mathbb{E}\left[\mathbf{V}([x', z'])\right] \\
&\downarrow \\
\mathbf{V}_1(s) &= \max_{x' \in \mathbf{B}(s)} \mathbf{F}(s, x') + \beta \mathbf{V}_2([x', s_2]) \\
\mathbf{V}_2(s) &= \mathbb{E}\left[\mathbf{V}_1([s_1, z'])\right]
\end{aligned}
$$

Approximation

- System to be solved on nodes s

$$\begin{aligned}
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- Replace functions with approximants

$$V_1(s_i) = \sum_{i=1}^{N_S} \phi(s_i) c_j^1 \qquad V_2(s_i) = \sum_{i=1}^{N_S} \phi(s_i) c_j^2$$

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\mathbf{V}_1(s) &= \Phi(s) c^1 \qquad \mathbf{V}_2(s) = \Phi(s) c^2
\end{aligned}$$

Approximation

- System to be solved on nodes s

$$\begin{aligned}\Phi(s)c^1 &= \max_{x' \in \mathbf{B}(s)} \mathbf{F}(s,x') + \beta\Phi([x', s_2])c^2 \\ \Phi(s)c^2 &= \mathbb{E}\left[\Phi([s_1, z'])c^1\right]\end{aligned}$$

- Replace functions with approximants

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Pre-computing integrals - Maliar, Maliar and Judd

$$\Phi(s)c^2 = \mathbb{E}\left[\Phi([s_1, z'])c^1\right]$$

$$\Phi\left(\begin{bmatrix} x_1 & z_1 \\ x_2 & z_1 \\ x_3 & z_1 \\ x_1 & z_2 \\ x_2 & z_2 \\ x_3 & z_2 \end{bmatrix}\right) c^2 = \begin{bmatrix} p_{11} & 0 & 0 & p_{12} & 0 & 0 \\ 0 & p_{11} & 0 & 0 & p_{12} & 0 \\ 0 & 0 & p_{11} & 0 & 0 & p_{12} \\ p_{21} & 0 & 0 & p_{22} & 0 & 0 \\ 0 & p_{21} & 0 & 0 & p_{22} & 0 \\ 0 & 0 & p_{21} & 0 & 0 & p_{22} \end{bmatrix} \Phi\left(\begin{bmatrix} x_1 & z_1 \\ x_2 & z_1 \\ x_3 & z_1 \\ x_1 & z_2 \\ x_2 & z_2 \\ x_3 & z_2 \end{bmatrix}\right) c^1$$

$$\Longrightarrow \Phi(s)c^2 = (\mathbf{P} \otimes \mathbf{I}_{N_X})\Phi(s)c^1$$

Solution

- $2N_S$ equations in $2N_S$ unknowns: $c = (c^{1\prime}, c^{2\prime})'$

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- Contains a $\max$ so any solution scheme must be iterative
  1. Contraction
  2. Newton-Raphson

Solution - Contraction

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1. Guess a $c_0 = (c_0^{1\prime}, c_0^{2\prime})$
2. Given c_k update to c_{k+1} by

$$c_{k+1}^1 = \Phi(s)^{-1}\left[\max_{x' \in \mathbf{B}(s)} \mathbf{F}(s, x') + \beta\Phi([x', s_2])c_k^2\right]$$

$$c_{k+1}^2 = \Phi(s)^{-1}(\mathbf{P} \otimes \mathbf{I}_{N_X})\Phi(s)c_k^1$$

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- Debug - Should *always* check this leads to convergence. It should if problem is a contraction and approximation is reasonable.

Solution - Newton Raphson

- $2N_S$ equations in $2N_S$ unknowns: $c = (c^{1\prime}, c^{2\prime})'$

$$\begin{aligned} \mathbf{g}(c) &= 0 \\ \begin{bmatrix} g_1\left(c^1, c^2\right) \\ g_2\left(c^1, c^2\right) \end{bmatrix} &= \begin{bmatrix} \Phi(s)c^1 - \max_{x' \in \mathbf{B}(s)} \mathbf{F}(s, x') + \beta\Phi([x', s_2])c^2 \\ \Phi(s)c^2 - (\mathbf{P} \otimes \mathbf{I}_{N_X})\Phi(s)c^1 \end{bmatrix} \end{aligned}$$

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Filling in the gaps - How to solve $\max$?

- Given a c we need to compute

$$\max_{x' \in \mathbf{B}(s)} \mathbf{F}(s, x') + \beta \Phi([x', s_2]) c^2$$

- Compecon function `goldenx` does vectorized golden-search. Robust. Fast.
- Simple to handle constraints $x' \in \mathbf{B}(s)$

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- What if x is multi-dimensional?

  Option 1 - Relatively straight-forward to write a Nelder-Mead algorithm. Can still keep everything vectorized.

  Option 2 - Use a FOC to pin down x_2 in terms of x_1, use golden-search on x_1.

  Option 3 - Use nested golden-search, one variable then the other.

Filling in the gaps - How to compute $\Phi(s)$?

- Compecon function `fundef` establishes a `fspace` object, for example ...
- Can then use the function `funbas` to compute basis matrices given `fspace` and any length vector x
- Compecon is nice because it's suitably general. Can jump back and forth between different approximation schemes (splines of different orders, Chebyshev etc).
- ...or write your own code. The main task in any collocation algorithm is computing basis matrices, over and over again.
- Can we avoid some of these computations?

Filling in the gaps - How to compute $\Phi(s)$?

- In the case of linear splines, the basis matrix $\Phi([x, z])$ is a tensor product.

$$\Phi([x, z]) = \Phi_Z(z) \circledast \Phi_X(x)$$

  where Φ_X is N_X wide and Φ_Z is N_Z wide.
- Looking at our problem note that we only have to compute $\Phi_Z(s_2)$ once.
- Each iteration of the solver for $\max_x'$ we need to do two things, (i) compute $\Phi_X(x')$ then take the tensor product with $\Phi_Z(s_2)$ to form $\Phi(s)$.
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- Warning The tensor products work *backwards*

$$\Phi([x,y,z]) = \Phi_Z(z) \circledast \Phi_Y(y) \circledast \Phi_X(x) = \text{dprod}(\Phi_Z(z), \text{dprod}(\Phi_Y(y), \Phi_X(x)))$$

Filling in the gaps - $x' \in \mathbf{B}(s)$

- Write a function which takes s as an argument and gives a vector of upper and lower bounds for x' depending on your problem
- These bounds then passed to solver

$$
\begin{aligned}
[\underline{x}, \bar{x}] &= \text{menufun}(\text{'bounds'}, s, \text{param}, \text{glob}, \text{options}) \\
\text{obj} &= @(x')\text{valfunc}(x', c, s, \text{param}, \text{glob}, \text{options}) \\
x' &= \text{goldenx}(\text{obj}, \underline{x}, \bar{x})
\end{aligned}
$$

Trial run - iid shocks to endogenous variable

1. Firm problem

$$V(k,z) = \max_{k' \in B(k,z)} F(k,z,k') + \sum_{z' \in \mathcal{Z}} P(z,z')\beta \int_{\underline{\eta}}^{\bar{\eta}} V(k'-\eta, z') dF(\eta)$$

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2. Re-write $s = (k,z)$ and split up

$$\begin{aligned} \mathbf{V}_1(s) &= \max_{x' \in \mathbf{B}(s)} \mathbf{F}(s,x') + \beta \mathbf{V}_2([x', s_2]) \\ \mathbf{V}_2(s) &= \mathbb{E}\left[\int_{\underline{\eta}}^{\bar{\eta}} \mathbf{V}_1([s_1 - \eta, z']) dF(\eta) \right] \end{aligned}$$

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3. Approximate iid shock with N_η nodes η with weights w

$$\mathbf{V}_2(s) = \mathbb{E}\left[\sum_{i=1}^{N_\eta} w_i \mathbf{V}_1([s_1 - \eta_i, z']) \right]$$

Trial run - iid shocks

4. Approximate value functions

$$\begin{aligned}
\Phi(s)c^1 &= \max_{x' \in \mathbf{B}(s)} \mathbf{F}(s, x') + \beta \Phi([x', s_2])c^2 \\
\Phi(s)c^2 &= \mathbb{E}\left[\sum_{i=1}^{N_\eta} w_i \Phi([s_1 - \eta_i, z'])c^1\right]
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5. Write expectations as matrix operation

$$\Phi(s)c^2 = (P \otimes \mathbf{I}_{N_X})(\mathbf{I}_{N_S} \otimes w')\Phi([s_1 \otimes \mathbf{i}_{N_\eta} - \mathbf{i}_{N_S} \otimes \eta\ ,\ s_2 \otimes \mathbf{i}_{N_\eta}])c^1$$

Trial run - Markov 'uncertainty' shocks

Household problem for uncertainty $i \in \{l, h\}$

$$V_i(a,e) = \max_{a' \in B(a,e)} F(a,e,a') + \beta \sum_{e' \in \mathcal{E}} P_i(e,e') \left[p_i V_i(a',e') + (1-p_i) V_j(a',e') \right]$$

Trial run - Markov 'uncertainty' shocks

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Re-write $s = (a,e)$ and split up

$$\begin{aligned}
V_1(s) &= \max_{x' \in \mathbf{B}(s)} \mathbf{F}(s,x') + \beta V_3([x', s_2]) \\
V_2(s) &= \max_{x' \in \mathbf{B}(s)} \mathbf{F}(s,x') + \beta V_4([x', s_2]) \\
V_3(s) &= \sum_{z' \in \mathcal{Z}} P_l(s_2,z') \left[p_l V_1([s_1,z']) + (1-p_l) V_2([s_1,z']) \right] \\
V_4(s) &= \sum_{z' \in \mathcal{Z}} P_h(s_2,z') \left[p_h V_2([s_1,z']) + (1-p_h) V_1([s_1,z']) \right]
\end{aligned}$$

Trial run - Markov 'uncertainty' shocks

Approximate value functions, write expectation as a matrix operation

$$
\begin{aligned}
\Phi(s)c^1 &= \max_{x' \in \mathbf{B}(s)} \mathbf{F}(s, x') + \beta \Phi(s) c^3([x', s_2]) \\
\Phi(s)c^2 &= \max_{x' \in \mathbf{B}(s)} \mathbf{F}(s, x') + \beta \Phi(s) c^4([x', s_2]) \\
\Phi(s)c^3 &= (\mathbf{P}_l \otimes \mathbf{I}_{N_X}) \left[p_l \Phi(s) c^1 + (1 - p_l) \Phi(s) c^2 \right] \\
\Phi(s)c^4 &= (\mathbf{P}_h \otimes \mathbf{I}_{N_X}) \left[p_h \Phi(s) c^2 + (1 - p_h) \Phi(s) c^1 \right]
\end{aligned}
$$

Proceed as above, slightly more complicated Jacobian

Trial run - Discrete choice

Firm problem for $i \in \{d, u\}$

$$V_i(k,z) = \max_{k' \in B_i(k,z)} F_i(k,z,k') + \beta \sum_{z' \in \mathcal{Z}} P(z,z') \max\{V_d(k',z'), V_u(k',z')\}$$

Trial run - Discrete choice

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Re-write $s = (k,z)$ and split up

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V_2(s) &= \max_{x' \in \mathbf{B}_u(s)} \mathbf{F}_u(s,x') + \beta V_3([x', s_2]) \\
V_3(s) &= \sum_{z' \in \mathcal{Z}} P(s_2,z') \max\{V_1([s_1,z']), V_2([s_1,z'])\}
\end{aligned}$$

Trial run - Discrete choice

Approximate value functions, write expectation as a matrix operation

$$\begin{aligned}
\Phi(s)c^1 &= \max_{x' \in \mathbf{B}_d(s)} \mathbf{F}_d(s,x') + \beta\Phi(s)([x', s_2])c^3 \\
\Phi(s)c^2 &= \max_{x' \in \mathbf{B}_u(s)} \mathbf{F}_u(s,x') + \beta\Phi(s)([x', s_2])c^3 \\
\Phi(s)c^3 &= (P \otimes \mathbf{I}_{N_X}) \max\left\{\Phi([s_1, z'])c^1, \Phi([s_1, z'])c^2\right\}
\end{aligned}$$

Trial run - AR(1) process for z

Firm problem

$$
\begin{aligned}
V(k,z) &= \max_{k' \in B(k,z)} F(k,z,k') + \beta \int V(k', g(z,\varepsilon)) d\Gamma(\varepsilon) \\
g(z,\varepsilon) &= \exp\left(\rho \log z + \varepsilon\right) \\
\varepsilon &\sim N(0, \sigma_\varepsilon)
\end{aligned}
$$

Trial run - AR(1) process for z

Firm problem

$$\begin{aligned} V(k,z) &= \max_{k' \in B(k,z)} F(k,z,k') + \beta \int V(k', g(z,\varepsilon)) d\Gamma(\varepsilon) \\ g(z,\varepsilon) &= \exp\left(\rho \log z + \varepsilon\right) \\ \varepsilon &\sim N(0, \sigma_\varepsilon) \end{aligned}$$

Proceed exactly as above for the iid case but approximating $\Gamma(\varepsilon)$ with a Gaussian quadrature scheme with N_ε nodes ε and weights w, arrive at

$$\begin{aligned} \Phi(s)c^1 &= \max_{x' \in \mathbf{B}(s)} \mathbf{F}(s,x') + \beta \Phi([x', s_2])c^2 \\ \Phi(s)c^2 &= (\mathbf{I}_{N_S} \otimes w')\Phi([s_1 \otimes \mathbf{i}_{N_\varepsilon},\ g(s_2 \otimes \mathbf{i}_{N_\varepsilon}, \mathbf{i}_{N_S} \otimes \varepsilon)])c^1 \end{aligned}$$

Stationary distribution

- Method of Young (2010), Gianluca discussed this last week
- Approximate the distribution λ with a fine histogram L
- Having solved the value function problem we have the expected value function
- Now given any (notation warning) s we can solve for $x'(s)$

- Choose a fine grid of s for approximation of the distribution
- Solve for $x'(s)$ by computing $\max_{x'} \mathbf{F}(s, x') + \beta\Phi([x', s_2])c^1$
- Let L be the approximate distribution, we want to use $x'(s)$ and P to generate a matrix Q such that the law of motion can be represented

$$L = Q'L$$

- Then either take out principle eigen vector of Q or iterate given a guess L^0

Stationary distribution - Q

- Construct Q by taking the tensor product of two matrices Q_X and Q_Z

$$Q = Q_Z \circledast Q_X$$

- The $N_S \times N_X$ matrix Q_X matrix uses $x'(s)$ to shift mass in terms of endogenous transitions
- The $N_S \times N_Z$ matrix Q_Z matrix *then* uses P to shift mass in terms of exogenous transitions

Stationary distribution - Q_X

- Given the approximating grid $x = (x_1, \ldots, x_{N_X})$, we compute

$$Q_X(s_i, x_j) = \left[\mathbf{1}_{x'(s_i) \in [x_{j-1}, x_j]} \frac{x'(s_i) - x_j}{x_j - x_{j-1}} + \mathbf{1}_{x'(s_i) \in [x_j, x_{j+1}]} \frac{x_{j+1} - x'(s_i)}{x_{j+1} - x_j} \right]$$

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- Note Useful in that aggregates will be unbiased!

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- Note When stacked, $Q_X = \Phi(x'(s))$ where Φ is basis matrix of linear-spline

$$\begin{aligned} fspaceQ_X &= fundef(\{spli, x, 0, 1\}) \\ Q_X &= funbas(fspaceQ_X, x'(s)) \end{aligned}$$

Stationary distribution - Q_Z

- The matrix Q_Z is easy to compute in the case of discrete transitions

$$Q_Z = \mathbf{P} \otimes \mathbf{i}_{N_X}$$

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- Something along these lines also works for iid shocks to $x'(s)$

Equilibrium - Bisection

- Given Q can compute approximation of stationary distribution L
- Then aggregate $\bar{x}(p)$ is

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- Bisection
  - Fix $(\underline{p}, \bar{p})$ and $p_0 = \frac{\underline{p}+\bar{p}}{2}$
  - If $\bar{x}(p_k) > \bar{x}$ set $(\underline{p}, \bar{p}) = (p_k, \bar{p})$
  - If $\bar{x}(p_k) < \bar{x}$ set $(\underline{p}, \bar{p}) = (\underline{p}, p_k)$

Equilibrium - Parallel Bisection

- Haven’t used parallel computing anywhere - only used one CPU
- If have more than one CPU then have idle resources
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$$\left[\underline{p}, p_1, \ldots, p_h, \bar{p}\right]$$

- Proceed as in bisection with a parallelised loop over $\{p_1, \ldots, p_h\}$
- Find the interval in which $\bar{x}(p) = \bar{x}$ and then set the lower and upper bounds to the end points of that interval

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- Note Particularly useful when the structure of the problem prevents you parallelising anything else, for example when computing period t equilibria for transition dynamics / Krussell-Smith

NYU - HPC

Resources

+ NYU HPC Wiki (Google it)
+ Some useful shell-script - HPCnotes.sh
+ Example pbs file - RUNsimple.pbs

NYU HPC

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  - A cluster of nodes, each node has up to 20 CPUs
  - Think of a node as a large desktop (show pbstop)

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Example - Model is indexed by $\theta \in \Theta$. **Aim** $\min_{\theta \in \Theta} \mathcal{C}(\theta)$

1. A hill-climbing algorithm (1-node $\times$ 1-CPU)
2. A random-search algorithm (20-node $\times$ 20-CPU)
3. MCMC (20-node $\times$ 1-CPU)

See: Appendix B4 of Jarosh (2014)

NYU HPC - Access

- Get your adviser to approve access
- Operating systems
  - Mac - Can access directly from terminal
  - Windows - Download Cygwin, add packages (openssh, vi, ...)
- Logging in
  - PC-to-HPC: ssh ab1234@hpc.nyu.edu
  - HPC-to-Mercer: ssh ab1234@mercer.es.its.nyu.edu
- Structure - /scratch /home
- Submitting jobs - Interactive mode / Batch processing
  - Work in interactive mode
  - Write a *.pbs file

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  - Matlab, Fortran, Git, Python, OpenMPI, Julia, R, Stata, Dynare, Nag, Lapack, Pandas, NumPy, SciPy ...

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- Move directory of Compecon files from PC-to-HPC-Mercer
  - From PC: scp -r Compecon sm4125@hpc.nyu.edu
  - From Mercer: scp sm4125@hpc.nyu.edu: /Compecon /scratch/sm4125
  - Don’t use WinSCP, it’s horrible
  - Use git to sync

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- Tip Since coding at the bash-script can be a pain, work from a text. Then copy over to prompt. Notepad++ marks up a .sh file nicely.