From many-body physics to financial markets: sparse modeling for inverse problems

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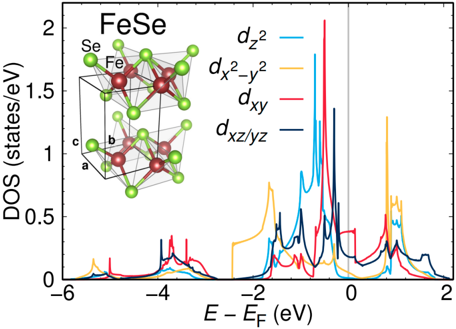
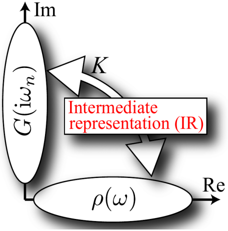
Density of states and Matsubara Green's function

- Electronic density of states describes behavior of material, e.g. spectroscopy
- Start with $\rho(E)$ from effective non-interacting theory
- Matsubara Green's function
  $G(i\omega_n) = \int_{-\infty}^{\infty} dE \, \frac{\rho(E)}{i\omega_n - E}$
  with $\omega_n = (2n+1)\pi/\beta$, $n \in \mathbb{Z}$
- Calculate interacting $G_{\text{int}}(i\omega_n)$ using $G(i\omega_n)$ and Feynman diagrams
- Compare $\rho_{\text{int}}(E)$ to experiments
- How to obtain $\rho_{\text{int}}(E)$ from $G_{\text{int}}(i\omega_n)$?

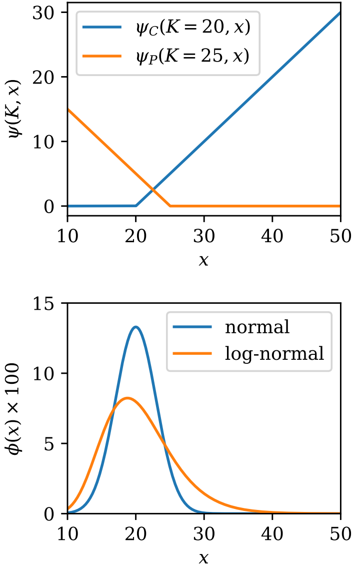




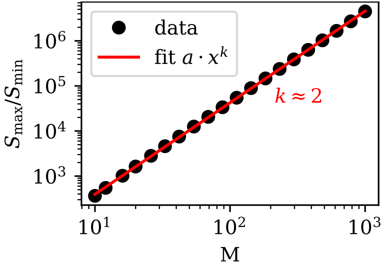
Figures: Comp. Phys. Commun. **231**, 114 (2018), JPSJ **89**, 012001 (2020)

Terminal density and plain-vanilla option price

- Price for option with payoff $\psi(K, x)$ and known terminal density $\phi(x)$:
  $$\Pr(K) = \int_{-\infty}^{\infty} dx\, \psi(K, x)\phi(x)$$
- Call option: $\psi_C(K, x) = \max(0, x - K)$
- Put option: $\psi_P(K, x) = \max(0, K - x)$
- Bachelier model: normal $\phi(x)$
- Black-Scholes model: log-normal $\phi(x)$
- Simple models do not match the market
- How to imply continuous $\phi(x)$ from discrete set of market prices $\Pr(K)$?



Linearization and singular value decomposition



- $\Pr(K) = \int_{-\infty}^{\infty} dx\, \psi(K,x)\phi(x)$
- M known prices
- N equidistant points in x-direction
- Trapezoidal approximation for integral
- $g_i(x) = \Delta x \cdot \psi_{C/P}(K_i, x)$

$$\Pr = \begin{pmatrix} \Pr_1 \\ \vdots \\ \Pr_M \end{pmatrix} = \begin{pmatrix} \frac{1}{2}g_1(x_1) & g_1(x_2) & \dots & g_1(x_{N-1}) & \frac{1}{2}g_1(x_N) \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \frac{1}{2}g_M(x_1) & g_M(x_2) & \dots & g_M(x_{N-1}) & \frac{1}{2}g_M(x_N) \end{pmatrix} \begin{pmatrix} \phi(x_1) \\ \vdots \\ \phi(x_N) \end{pmatrix} = G\phi$$

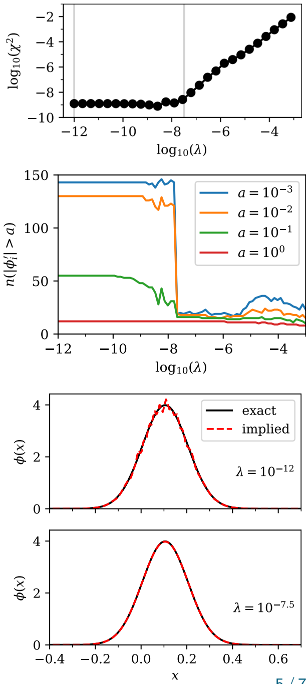
- In general G is $M \times N$ matrix, with $M \leqslant N$
- G is ill-conditioned, cannot invert $\Pr = G\phi$ to get ϕ
- Analyze kernel with singular value decomposition: $G = USV^T$
- Singular values decay quadratically, makes inversion unstable

Figures: arXiv:2205.10865

SVD, optimization, regularization

- SVD: $\mathrm{Pr} = G\phi = USV^T\phi$
- $\mathrm{Pr}' = U^T\mathrm{Pr} = SV^T\phi = S\phi'$
- S is diagonal, $\mathrm{Pr}'_i = S_{ii}\phi'_i = s_i\phi'_i$
- Keep Q singular values: $(U, V) \to (\tilde{U}, \tilde{V})$
- $\tilde{U}$ is $M \times Q$ with $Q \leqslant \min(M, N)$, approximate $G \approx \tilde{G} = \tilde{U}\tilde{S}\tilde{V}^T$
- L_1-regularized optimization problem $F(\phi'|\mathrm{Pr}, \lambda) = \frac{1}{2}\|\mathrm{Pr} - \tilde{U}\tilde{S}\phi'\|_2^2 + \lambda\|\phi'\|_1$
- N discretization points for ϕ, but optimize only $Q \leqslant \min(M, N)$ entries of ϕ'
- additional conditions $\phi_i = \left(\tilde{V}\phi'\right)_i \geqslant 0 \quad \forall i$

and $1 = \left(\frac{1}{2}(\phi_1 + \phi_N) + \sum_{i=2}^{N-1} \phi_i\right)\Delta x$



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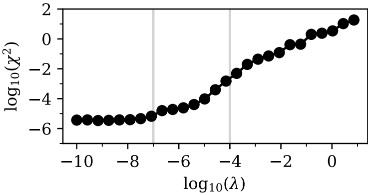
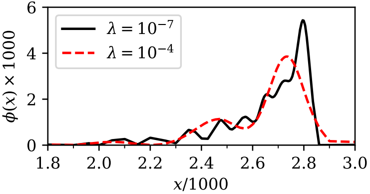
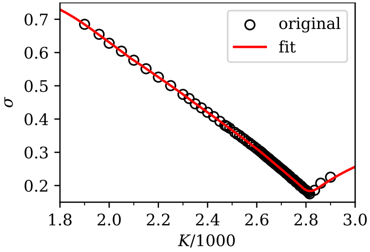
S&P 500 index options

- Perfect reproduction of normal (Bachelier), mixtures of normal and log-normal (Black-Scholes) models
- One-month S&P 500 index options on February 5th, 2018
- Calculate implied future distribution of stock index price
- Automatically correct implied volatility smiles
- Sensible inter- and extrapolation, currently no other general method available
- Performance easily tunable by choice of Q and N, execution time $\sim$ 10 ms







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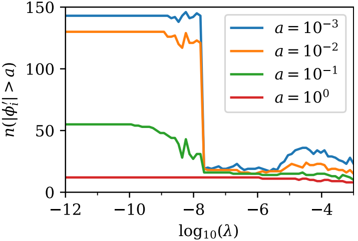
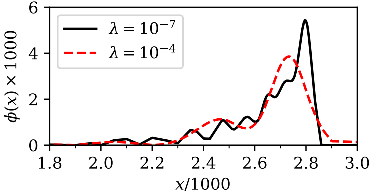
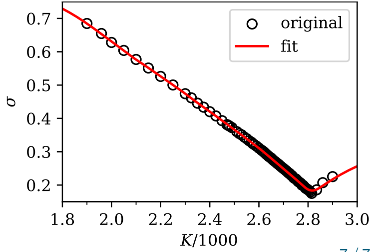
Summary

- Want to find density $\phi(x)$ in integral
  $$\Pr(K) = \int_{-\infty}^{\infty} dx\, \psi(K, x)\phi(x)$$
- Approximate integral using trapezoidal rule, write as matrix equation
- Perform SVD of kernel matrix
- Discard small singular values
- Reformulate as optimization problem in SVD-transformed domain
- Apply L_1-regularization to parameters
- General recipe for ill-conditioned inverse problems of this form
- Solution to the problem of volatility smile interpolation and extrapolation







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References

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- Guterding & Jeschke, Comp. Phys. Commun. **231**, 114 (2018)
- Guterding, arXiv:2205.10865