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Least squares hedge for exotic options

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Introduction

1 Introduction

- Hedging is a core part financial risk management
- Institutions that agree to be a counterparty to a contract might not wish carry the associated risk
- This risk is often hedged with a dynamic replicating portfolio
 - Model dependent
 - Labor intensive
- This thesis presents a method for finding a static replicating portfolio as an alternative for a dynamic replicating portfolio

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Dynamic hedging of vanilla options

2 Black-Scholes equation

- Assume the stock price process follows the geometric Brownian motion

$$dS_t = \mu S_t dt + \sigma S_t dB_t,$$

where μ is the drift, σ is the volatility and dB_t is the Brownian motion.

- Black and Scholes¹ show that the call option price process C is governed by the partial differential equation

$$\frac{\partial C}{\partial t} + rS_t \frac{\partial C}{\partial S} + \frac{1}{2}\sigma^2 S_t^2 \frac{\partial^2 C}{\partial S^2} = rC$$

¹F. Black and M. Scholes, "The pricing of options and corporate liabilities," Journal of political economy, vol. 81, no. 3, pp. 637–654, 1973.

2 Black-Scholes formula

- To find the option price function C the Black-Scholes PDE needs to be solved with appropriate boundary conditions

$$C(K, T, \sigma; t, 0) = 0 \quad \forall t$$

$$\lim_{S_t \rightarrow \infty} C(K, T, \sigma; t, S_t) = \lim_{S_t \rightarrow \infty} S_t - K \exp(-r(T-t)) \quad \forall t$$

$$C(K, T, \sigma; T, S_T) = \max\{0, S_T - K\} \quad \forall S_T$$

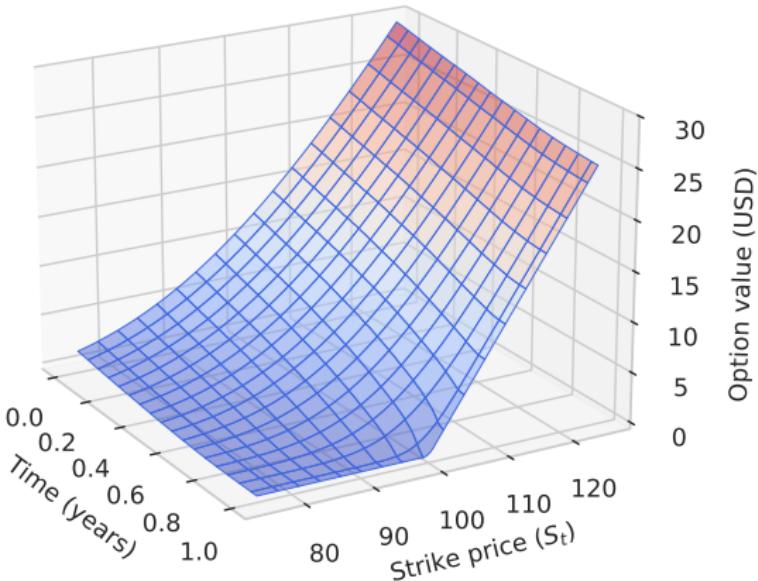
- The solution is known as the Black-Scholes formula

$$C(K, T, \sigma; t, S_t) = S_t \mathcal{N}(d_+) - K \exp(-r(T-t)) \mathcal{N}(d_-)$$

$$d_{\pm} = \frac{\ln(S_t/K) + (r \pm \frac{1}{2}\sigma^2)(T-t)}{\sigma\sqrt{T-t}}$$

$$\mathcal{N}(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^z \exp\left(-\frac{1}{2}y^2\right) dy$$

2 Option price surface



2 Dynamic replicating portfolio

- Consider a portfolio Π consisting of x units of the stock S_t and y units of risk-free bond

$$\Pi = xS_t + ye^{rt}$$

- The portfolio has partial derivatives

$$\frac{\partial \Pi}{\partial t} = yre^{rt}, \quad \frac{\partial \Pi}{\partial S} = x, \quad \frac{\partial^2 \Pi}{\partial S^2} = 0$$

- Placing the partial derivatives into the Black-Scholes equation yields

$$\begin{aligned}\frac{\partial \Pi}{\partial t} + rS_t \frac{\partial \Pi}{\partial S} + \frac{1}{2}\sigma^2 S_t^2 \frac{\partial^2 \Pi}{\partial S^2} &= r\Pi \\ yre^{rt} + rS_t x + 0 &= r(xS_t + ye^{rt})\end{aligned}$$

- Thus, an issued option can be hedged by forming a *dynamic replicating portfolio* of the underlying asset and the risk-free bond

2 Sensitivities

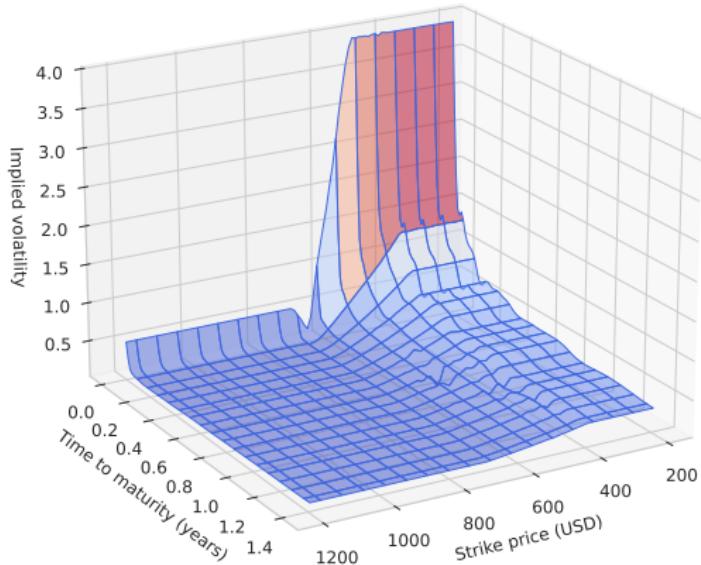
- The most common hedge is the *delta hedge*, where the sensitivity to the change in the value of the underlying is eliminated
- Assume a market maker has issued a call option. By going long on $\Delta = \frac{\partial C}{\partial S}$ units of the underlying the portfolios value will not change for infinitesimal changes in the underlying asset's value
- Other commonly considered sensitivities are

$$\nu = \frac{\partial C}{\partial \sigma}, \quad \Gamma = \frac{\partial^2 C}{\partial S^2}, \quad \rho = \frac{\partial C}{\partial r}, \quad \text{etc.}$$

2 Implied volatility and model parameters

- The Black-Scholes formula requires two parameters - the risk-free rate r and the volatility σ
 - Depending on the trader the risk-free rate could be e.g. some short-term rate (ESTR), interbank offered rate (EURIBOR) or government bond yield (BUND, SCHATZ, BOBL)
 - Volatility is less clear. Black and Scholes define it as the standard deviation of the historical stock returns
 - Alternatively, it can be calculated based on observed market prices → *implied volatility*
-

2 Implied volatility surface



3

Dynamic hedging of exotic options

3 State prices

- Arrow and Debreu² define the so called Arrow-Debreu security (elementary claim in Breeden and Litzenberger's work) as a contract that pays unit amount of some numeraire if a particular state occurs at a predefined time
- Let S_T be a random variable giving one of the possible n states in set $\mathcal{S} = \{s_T^{(1)}, s_T^{(2)}, \dots, s_T^{(n)}\}$. An Arrow-Debreu security on state $s_T^{(i)}$ has the payoff

$$v^{(i)}(T, S_T) = \begin{cases} 1, & S_T = s_T^{(i)} \\ 0, & \text{otherwise} \end{cases}$$

- The present value of $v^{(i)}(t, S_t)$ of the Arrow-Debreu security is known as the *state price*

²K. J. Arrow and G. Debreu, "Existence of an equilibrium for a competitive economy," *Econometrica*, vol. 22, no. 3, pp. 265—290, 1954

3 State prices example

- Assume the future states are tied to the results of some sport's game, which can end in one of two ways
 - Home team wins and the away team loses
 - Away team wins and the home team loses
- Denote these states by $s_T^{(H)}$ and $s_T^{(A)}$ respectively
- The random variable S_T associates a probability for both states as
 $\mathbb{P}[S_T = s_T^{(H)}] = p_H$ and $\mathbb{P}[S_T = s_T^{(A)}] = p_A$
 - States are mutually exclusive and collectively exhaustive

3 State prices example

- Assume an investor buys Arrow-Debreu securities for both states $s_T^{(H)}$ and $s_T^{(A)}$
- This guarantees unit payoff meaning

$$v^{(H)}(t, S_t) + v^{(A)}(t, S_t) = e^{-r(T-t)} = e^{-r(T-t)}(w_H + w_A),$$

where $w_H > 0$, $w_A > 0$ and $w_H + w_A = 1$

- Arrow and Debreu propose that the state price is directly proportional to the probability of the state occurring. Thus

$$v^{(H)}(t, S_t) = e^{-r(T-t)} p_H \propto p_H \text{ and } v^{(A)}(t, S_t) = e^{-r(T-t)} p_A \propto p_A$$

3 State prices

- More generally, with a set S of n states

$$v^{(i)}(t, S_t) = e^{-r(T-t)} \mathbb{P}[S_T = s_T^{(i)}]$$

- The present value of a state-contingent claim on the states in the set S is then

$$E(T; t, S_t) = \sum_{i=1}^n E(T; T; s_T^{(i)}) v^{(i)}(t, S_t)$$

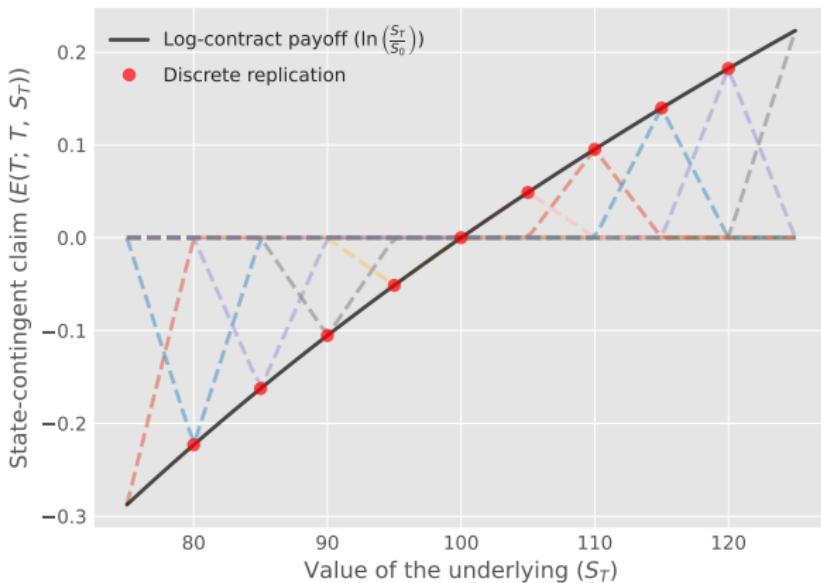
3 Breeden-Litzenberger

- Let the set of possible future states of a random variable S_t be $\mathcal{S} = \{s \in \mathbb{R} | s \geq 0\}$ (non-negative real line)
- Assume there exists call options with strike prices for each of the states in set \mathcal{S}
- Breeden and Litzenberger³ propose using three call options with strikes $K - dS_t$, K and $K + dS_t$ for some small and positive dS_t to form a portfolio

$$e(K, t, \sigma; t, S_t) = \frac{C(K - dS_t, T, \sigma; t, S_t) - 2C(K_t, T, \sigma; t, S_t) + C(K + dS_t, T, \sigma; t, S_t)}{dS_t}$$

³D. T. Breeden and R. H. Litzenberger, "Prices of state-contingent claims implicit in option prices," Journal of business, pp. 621-651, 1978

3 Breeden-Litzenberger



3 Breeden-Litzenberger

- In the limit $dS_t \rightarrow 0$ the value of the portfolio e approaches an Arrow-Debreu security
- Breeden and Litzenberger observed that in the limit

$$\lim_{dS_t \rightarrow 0} \frac{e(K, T, \sigma; t, S_t)}{dS_t} = \frac{\partial^2 C}{\partial S^2} = \Gamma$$

3 Breeden-Litzenberger

- Let $E(T; t, S_t)$ be a function giving the value of an exotic option
- The exotic option has a known state-contingent claim $E(T; T, S_T)$ and potentially some cashflows or boundary conditions for $t < T$
- The value of the option is given by

$$E(T; t, S_t) = \int_t^T \int_0^\infty E(\tau; \tau, K) \frac{\partial^2 C(K, \tau, \sigma; t, S_t)}{\partial S^2} dK d\tau$$

- The sensitivities of the exotic option can be calculated from the above expression and are denoted by

$$\Delta^{(BL)} = \frac{\partial E}{\partial S}, \quad \nu^{(BL)} = \frac{\partial E}{\partial \sigma}, \quad \text{etc.}$$

3 Implied volatilities and option implied probability density

- For the price E to fully reflect the market expectations, the volatility term in the integrand should vary with the maturity date and the strike price.
- This leads to expression

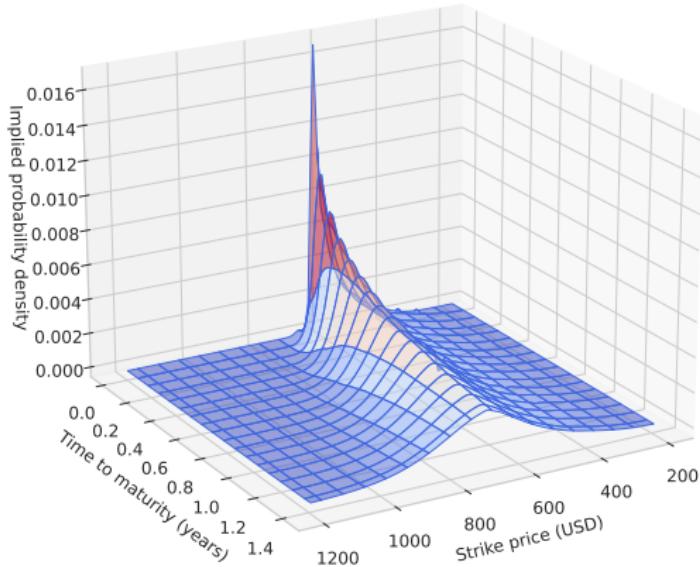
$$E(T; t, S_t) = \int_t^T \int_0^\infty E(\tau; \tau, K) \frac{\partial^2 C(K, \tau, \sigma_I(\tau, K); t, S_t)}{\partial S^2} dK d\tau$$

- Above expression also results in

$$\mathbb{P}[S_T = K] \propto \frac{\partial^2 C(K, \tau, \sigma_I(\tau, K); t, S_t)}{\partial S^2},$$

which is known as the *option implied probability density*

3 Option implied probability density surface



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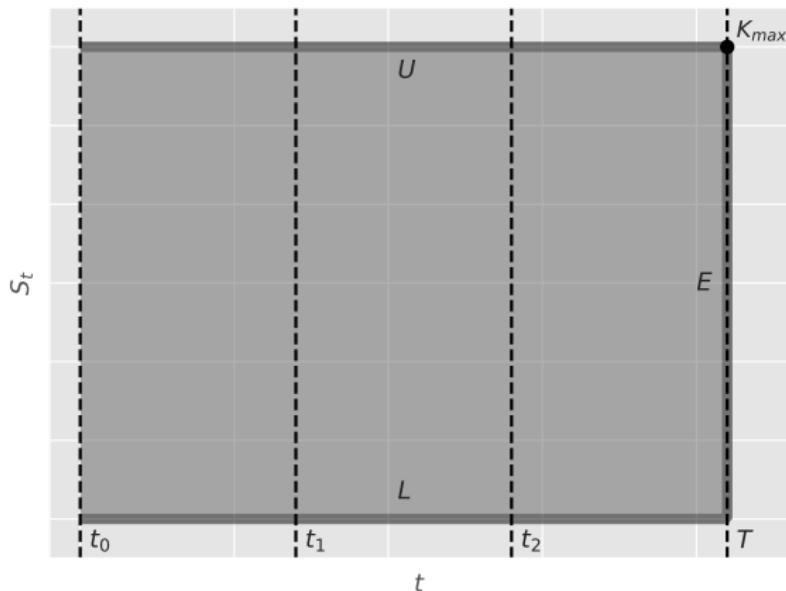
Static option replication

4 Static option replication

- Derman, Ergener and Kani⁴ propose a static hedge for exotic options defined by boundary conditions
- This hedge is found by replicating the boundaries using vanilla options
 - Since the exotic option is governed by the same dynamic (Black-Scholes PDE) as the vanilla options this provides a sufficient hedge
- The static hedge is found by backward induction and matching the boundary values at the nodes with the target value by buying or selling OTM call and put options

⁴E. Derman, D. Ergener, and I. Kani, "Static options replication," *Journal of Derivatives*, vol. 2, no. 4, pp. 1-37, 2000

4 Static option replication

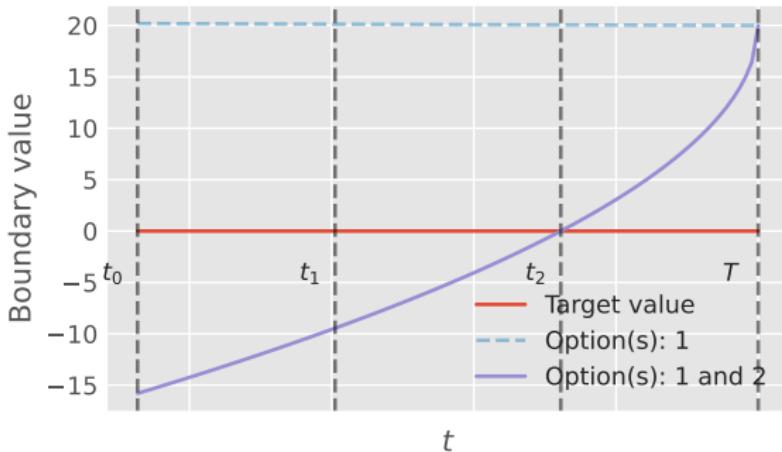


4 Up-and-out call option as an example

ID	K	Mat.	$C(0, 100)$	$C(0, 120)$	$C(7, 120)$	$C(14, 120)$	$C(21, 120)$
1	100	$T = 21$	3.032	20.191	20.121	20.056	20
2	120	$T = 21$	0.019	3.638	2.990	2.028	0
3	120	$t_2 = 14$	~ 0	2.990	2.170	0	0
4	120	$t_1 = 7$	~ 0	2.028	0	0	0

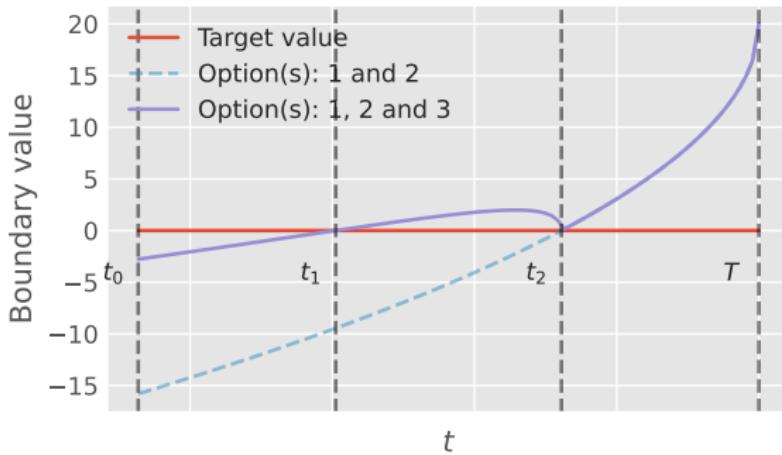
- Goal is to form an efficient hedge for an up-and-out option with strike 100, barrier at 120 and 21 periods (days to maturity)
- Initially $\#_1 = 1$ units of option one is purchased two match the termination boundary

4 Up-and-out call option as an example



- To match the target value at period t_2
 $\#_2 = -20.056 \cdot \#_1 / 2.028 = -9.890$ units of option two must be purchased

4 Up-and-out call option as an example



- To match the target value at period t_1
 $\#_3 = -(20.121 \cdot \#_1 + 2.990 \cdot \#_2) / 2.170 = 4.355$ units of option three must be purchased

4 Up-and-out call option as an example



- To match the target value at period t_0
 $\#_4 = -(20.191 \cdot \#_1 + 3.638 \cdot \#_2 + 2.990 \cdot \#_3) / 2.028 = 1.365$ units of option four must be purchased

5

Least squares hedge

5 Least squares hedge

- Let $\mathcal{K} = \{K_1, K_2, \dots, K_n\}$ be a set of strike prices for options $C^{(i)}$ available in the markets
- Goal is to find weights $\mathbf{x} \in \mathbb{R}^n$ that minimize the distance between the boundary values of the replicating portfolio and the target exotic option
 - There are at most three boundaries U (upper), L (lower) and E (termination)

5 Least squares hedge for path-independent exotic options

- Consider a path-independent exotic defined purely by the termination boundary with state-contingent claim E
- The state-contingent claim and available call options can be discretized into d points as $\mathbf{E} \in \mathcal{S}^d$ and $\mathbf{C}^{(i)} \in \mathcal{S}^d$
- The weights \mathbf{x} can be found by solving the optimization problem

$$\begin{aligned}\min_{\mathbf{x}} \quad & \|A\mathbf{x} - \mathbf{E}\|_2^2 \\ \text{s.t.} \quad & \mathbf{x} \in \mathbb{R}^n,\end{aligned}$$

where $A = [\mathbf{C}^{(1)} \quad \mathbf{C}^{(2)} \quad \dots \quad \mathbf{C}^{(n)}]$

5 Least squares hedge for path-dependent exotic options

- Extending the least squares hedge to path-dependent exotic options requires considering the upper U and lower L boundaries as well
 - Termination boundary discretized with respect to strike price
 - Upper and lower boundaries discretized with respect to time
- Assume there are N options with both calls and puts available. Further assume these are valid in the context of static option replication
- Least squares hedge is found by solving the linear system

$$Ax = \begin{bmatrix} C_E^{(1)} & C_E^{(2)} & \dots & P_E^{(N)} \\ C_L^{(1)} & C_L^{(2)} & \dots & P_L^{(N)} \\ C_U^{(1)} & C_U^{(2)} & \dots & P_U^{(N)} \end{bmatrix} x = \begin{bmatrix} E \\ L \\ U \end{bmatrix},$$

via linear least squares

5 Up-and-out call option revisited

- Consider the up-and-out call option example used to show case static option replication
- Using the exact same discretization leads to a linear system of equation

$$\begin{bmatrix} 20 & 0 & 0 & 0 \\ 20.056 & 2.028 & 0 & 0 \\ 20.121 & 2.990 & 2.170 & 0 \\ 20.191 & 3.638 & 2.990 & 2.028 \end{bmatrix} \mathbf{x} = \begin{bmatrix} 20 \\ 0 \\ 0 \\ 0 \end{bmatrix} \rightarrow \mathbf{x} = \begin{bmatrix} 1 \\ -9.890 \\ 4.355 \\ 1.365 \end{bmatrix}$$

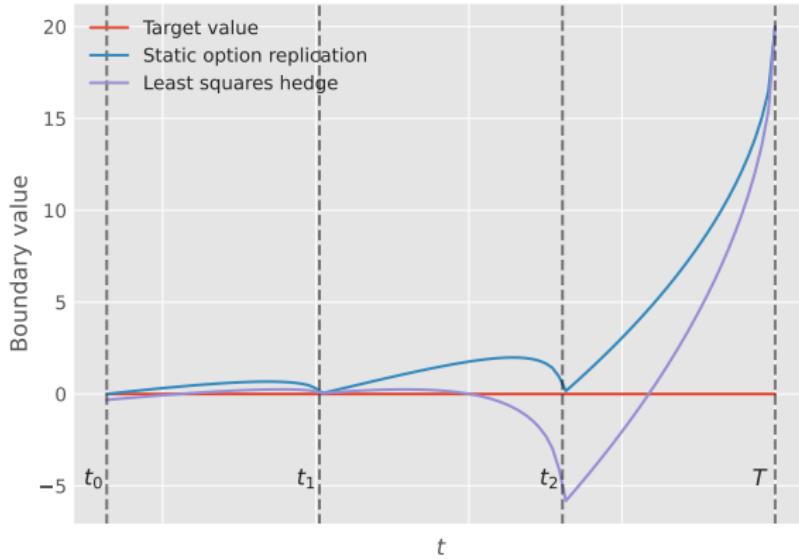
- Note that as the system was solvable iteratively it must be a triangular system

5 Up-and-out call option revisited

- Instead of being limited to the few discretization points, the least squares hedge can be applied to an arbitrary discretization
- Let the interval $[t_0, T]$ be discretized into 100 uniformly distributed points
- The solution vector is then

$$\mathbf{x}' = \begin{bmatrix} 1 \\ -12.864 \\ 8.465 \\ 0.484 \end{bmatrix}$$

5 Up-and-out call option revisited



6

Case study on the log-contract

6 Log-contract

- Neuberger⁵ presented the *log-contract* as a financial instrument for speculating volatility
- The payoff of the log-contract is defined as

$$E_{\log}(T; T, S_T) = \ln(S_T/S_0)$$

- Neuberger showed that the present value of the profit from delta-hedged position in the log-contract is (almost exactly) equal to

$$0.5(\sigma_I^2 - \sigma_T^2)T,$$

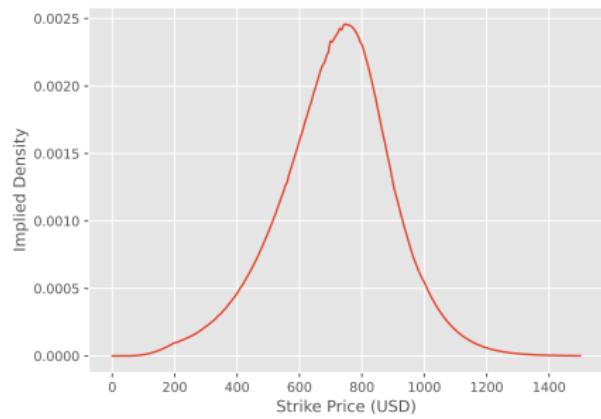
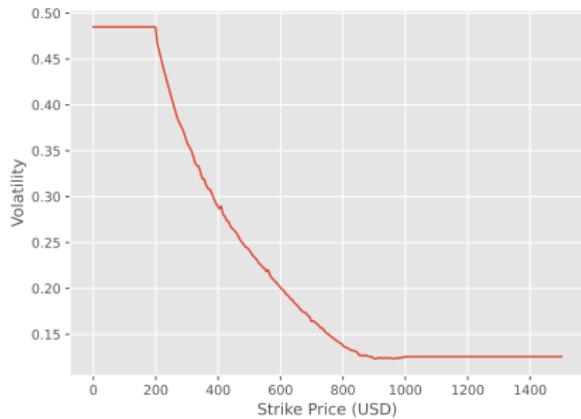
where σ_I is the volatility implied by the log-contract and σ_T is the outcome volatility

⁵A. Neuberger, "The log contract," Journal of portfolio management, vol. 20, no. 2, pp. 74-80, 1994

6 Dataset

- Dataset consists of options on SPDR S&P 500 ETF (\$SPY) maturing on 2027-12-17
 - 157 different options
 - Strikes varying from 200 USD to 1000 USD
- Option prices were quoted after market close on 2025-08-15

6 Dataset



6 Neuberger

- Under Black-Scholes assumptions the fair value of the log-contract is

$$E_{log}^{(N)}(T; t, S_t) = \ln(S_t/S_0) - 0.5\sigma^2(T - t)$$

- The sensitivities under Neuberger model are defined as

$$\Delta_{log}^{(N)} = \frac{\partial E_{log}}{\partial S_t} = \frac{1}{S_t}$$

$$\nu_{log}^{(N)} = \frac{\partial E_{log}}{\partial \sigma} = -\sigma(T - t)$$

Sensitivity	Price	Δ	ν
Value	-0.0419	0.0015	-0.4421

6 Breeden-Litzenberger

- Breeden-Litzenberger model is used as an alternative pricing method
- Unlike Neuberger model Breeden-Litzenberger model can utilize full volatility curve → takes the market expectations better into account

Sensitivity	Price	Δ	ν
Value	0.0725	0.0012	-0.2760

6 Least squares hedge

- Assume a market maker has issued a log-contract
 - Contract was priced with Breeden-Litzenberger model
 - Now the market maker is looking for a hedge. To limit vega-risk static hedge would be optimal

Sensitivity	Price	Δ	ν
Value	0.0219	0.0015	-0.2831

- Most of the risk eliminated
- Importantly, the hedge is cheaper than the contract

6 Residual risk

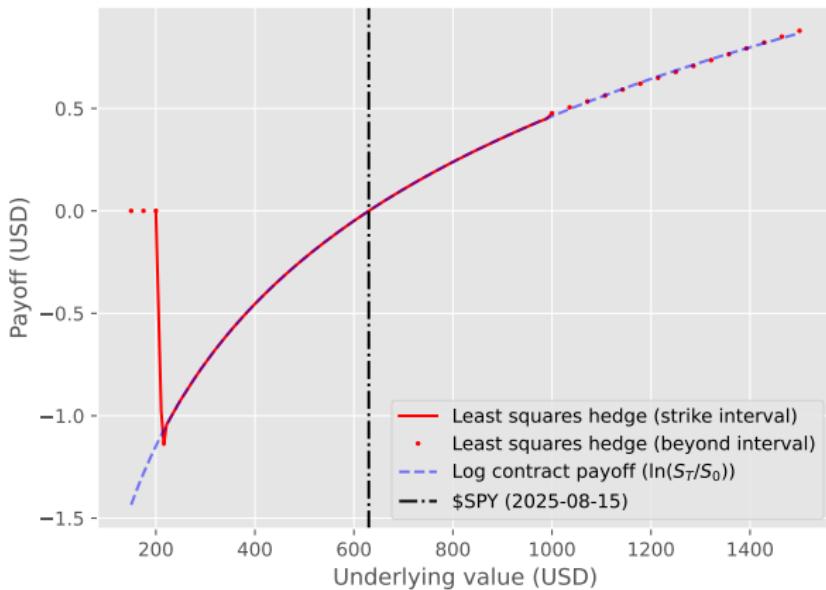
- While most of the delta- and vega-risk was eliminated the hedge only holds on a finite interval
- How likely is it that the underlying will go beyond this interval?
- Using the option implied probability density

$$\mathbb{P}[S_T < 200] = 0.0048$$

$$\mathbb{P}[S_T > 1000] = 0.0503$$

- However, the hedge doesn't fail catastrophically if $S_T > 1000$

6 Residual risk



7

Conclusions

7 Conclusions

- The case study shows the effectiveness of the least squares hedge
 - Most of the risk eliminated
 - Low cost → potential arbitrage?
 - Clear improvement over static option replication
- However, the effectiveness of the hedge can be impacted
 - Most stocks are more limited with regards to maturity days and strike prices than the case study
 - Model dependency remains an issue with path-dependent exotic options
 - Not all exotic options can be hedged (lookback, Asian, etc.)
- Overall, the least squares hedge can be a useful tool in conjunction with the dynamic replicating portfolio