

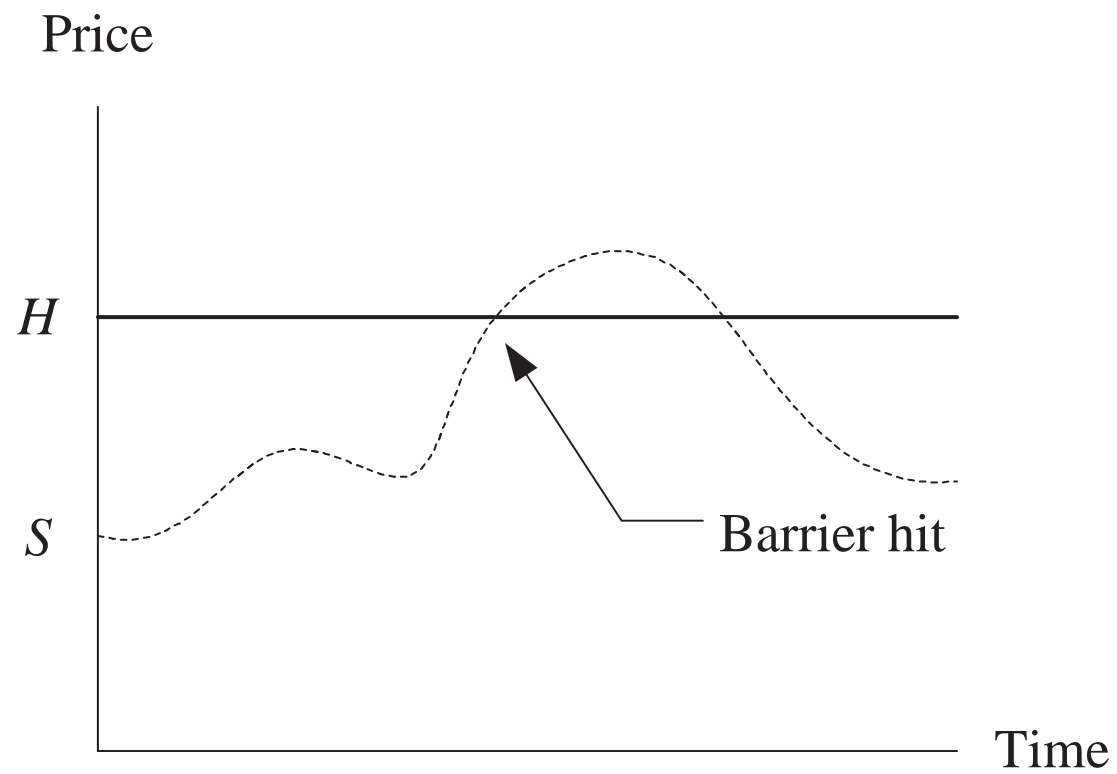
Other Examples

- Subordinated debts as bull call spreads.
- Warrants as calls.
- Callable bonds as American calls with 2 strike prices.
- Convertible bonds.

Barrier Options^a

- Their payoff depends on whether the underlying asset's price reaches a certain price level H .
- A knock-out option is an ordinary European option which ceases to exist if the barrier H is reached by the price of its underlying asset.
- A call knock-out option is sometimes called a down-and-out option if $H < S$.
- A put knock-out option is sometimes called an up-and-out option when $H > S$.

^aA former finance student told me on March 26, 2004, that she did not understand why I covered barrier options until she started working in a bank. She was working for Lehman Brothers in HK as of April, 2006.



Barrier Options (concluded)

- A knock-in option comes into existence if a certain barrier is reached.
- A down-and-in option is a call knock-in option that comes into existence only when the barrier is reached and $H < S$.
- An up-and-in is a put knock-in option that comes into existence only when the barrier is reached and $H > S$.
- Formulas exist for all the possible barrier options mentioned above.

A Formula for Down-and-In Calls^a

- Assume $X \geq H$.
- The value of a European down-and-in call on a stock paying a dividend yield of q is

$$Se^{-q\tau} \left(\frac{H}{S}\right)^{2\lambda} N(x) - Xe^{-r\tau} \left(\frac{H}{S}\right)^{2\lambda-2} N(x - \sigma\sqrt{\tau}), \quad (28)$$

$$- \quad x \equiv \frac{\ln(H^2/(SX)) + (r - q + \sigma^2/2)\tau}{\sigma\sqrt{\tau}}.$$

$$- \quad \lambda \equiv (r - q + \sigma^2/2)/\sigma^2.$$

- A European down-and-out call can be priced via the in-out parity (see text).

^aMerton (1973).

A Formula for Up-and-In Puts^a

- Assume $X \leq H$.
- The value of a European up-and-in put is

$$Xe^{-r\tau} \left(\frac{H}{S}\right)^{2\lambda-2} N(-x + \sigma\sqrt{\tau}) - Se^{-q\tau} \left(\frac{H}{S}\right)^{2\lambda} N(-x).$$

- Again a European up-and-out put can be priced via the in-out parity.

^aMerton (1973).

Are American Options Barrier Options?^a

- It looks like American options are barrier options with the exercise boundary treated as the barrier and the payoff as the rebate.
- One salient difference is that the exercise boundary must be derived during backward induction.
- On the other hand, the barrier in a barrier option is given a priori.

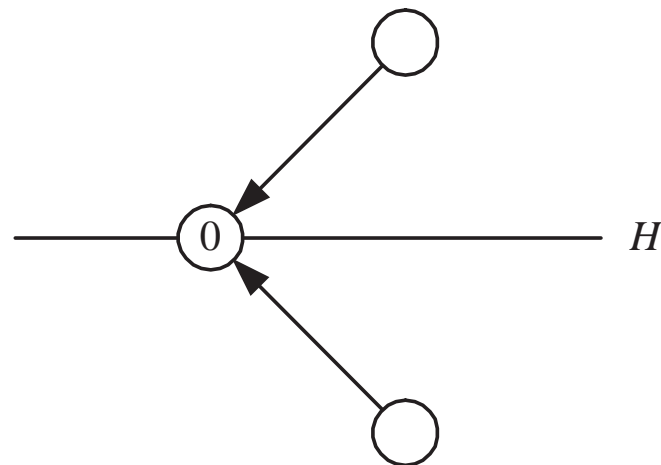
^aContributed by Mr. Yang, Jui-Chung (D97723002) on March 25, 2009.

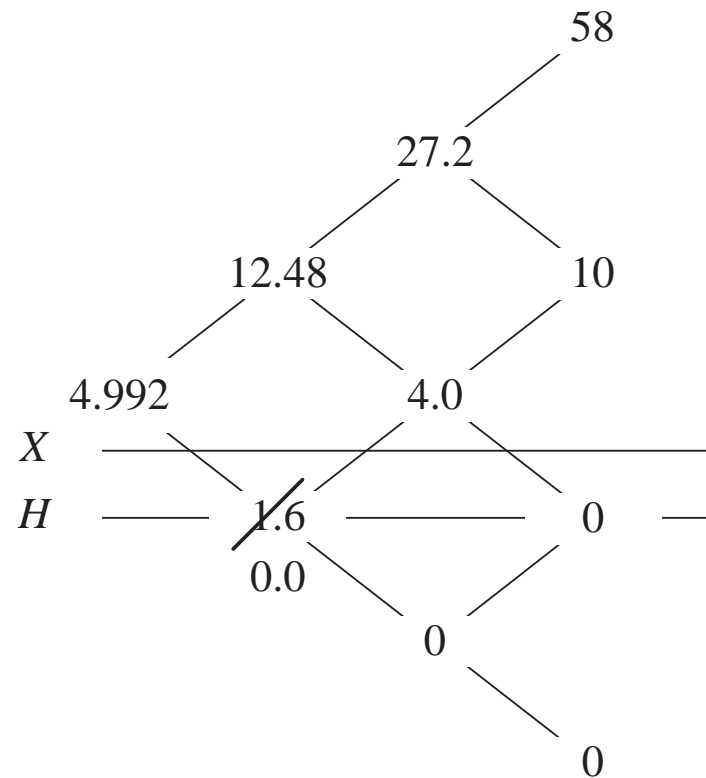
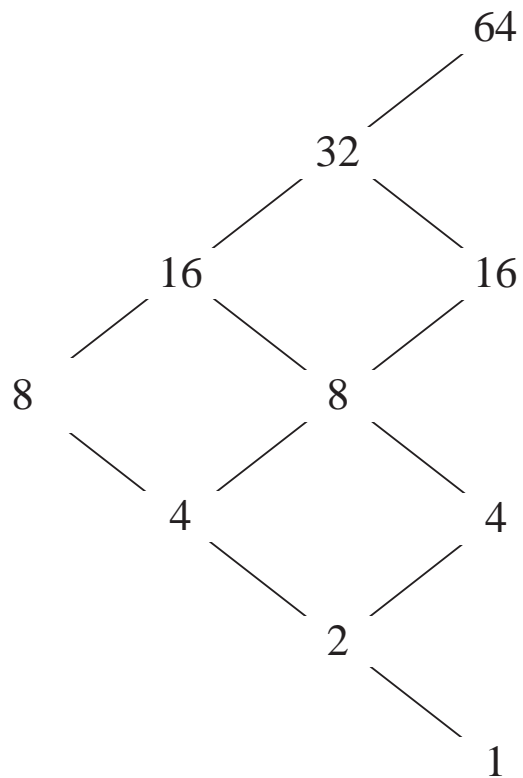
Interesting Observations

- Assume $H < X$.
- Replace S in the pricing formula for the down-and-in call, Eq. (28) on p. 320, with H^2/S .
- Equation (28) becomes Eq. (25) on p. 272 when $r - q = \sigma^2/2$.
- Equation (28) becomes S/H times Eq. (25) on p. 272 when $r - q = 0$.
- Why?

Binomial Tree Algorithms

- Barrier options can be priced by binomial tree algorithms.
- Below is for the down-and-out option.





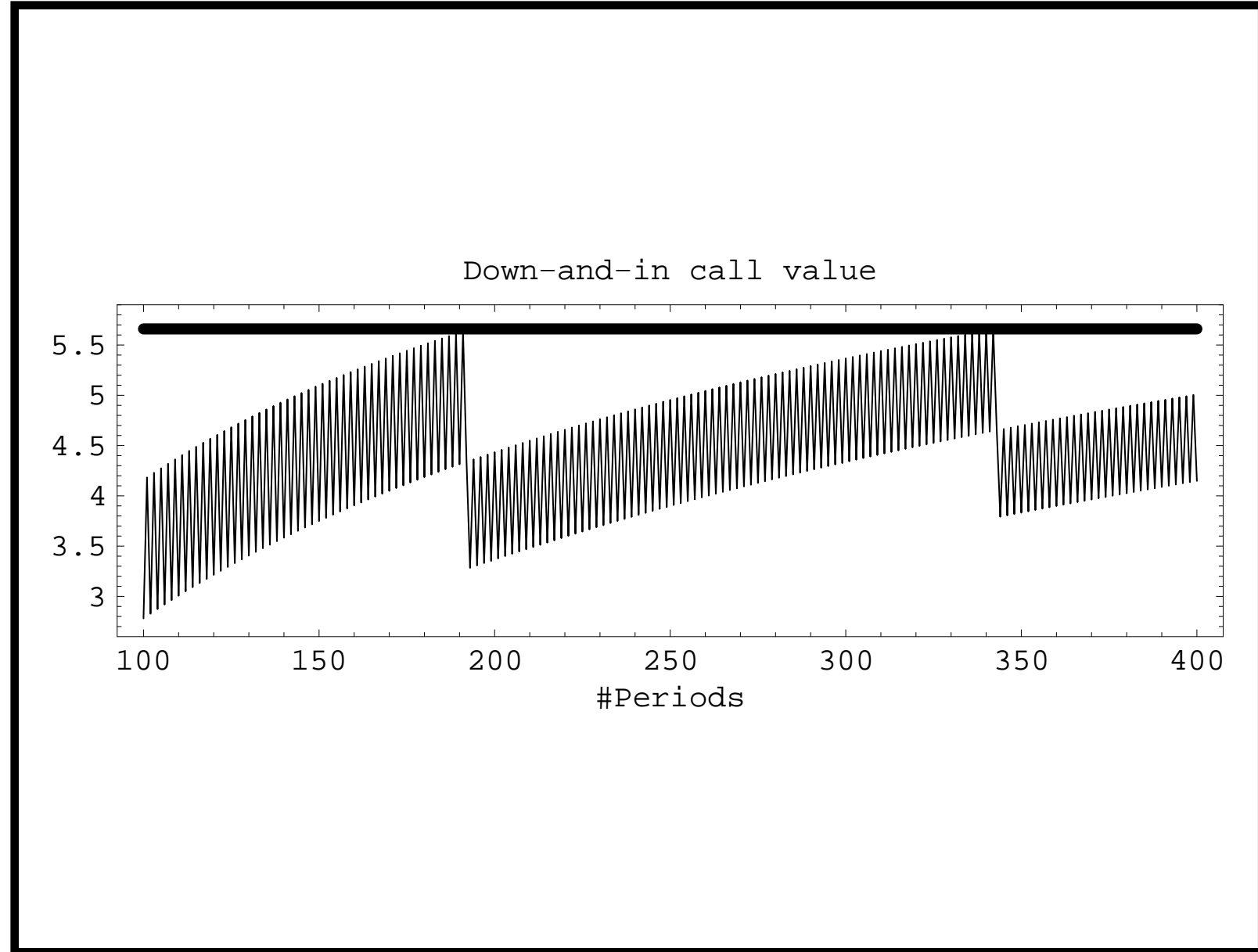
$S = 8$, $X = 6$, $H = 4$, $R = 1.25$, $u = 2$, and $d = 0.5$.

Backward-induction: $C = (0.5 \times C_u + 0.5 \times C_d)/1.25$.

Binomial Tree Algorithms (concluded)

- But convergence is erratic because H is not at a price level on the tree (see plot on next page).
 - The barrier has to be adjusted to be at a price level.
 - The “effective barrier” changes as n increases.
- In fact, the binomial tree is $O(1/\sqrt{n})$ convergent.^a
- Solutions will be presented later.

^aLin (R95221010) (2008).

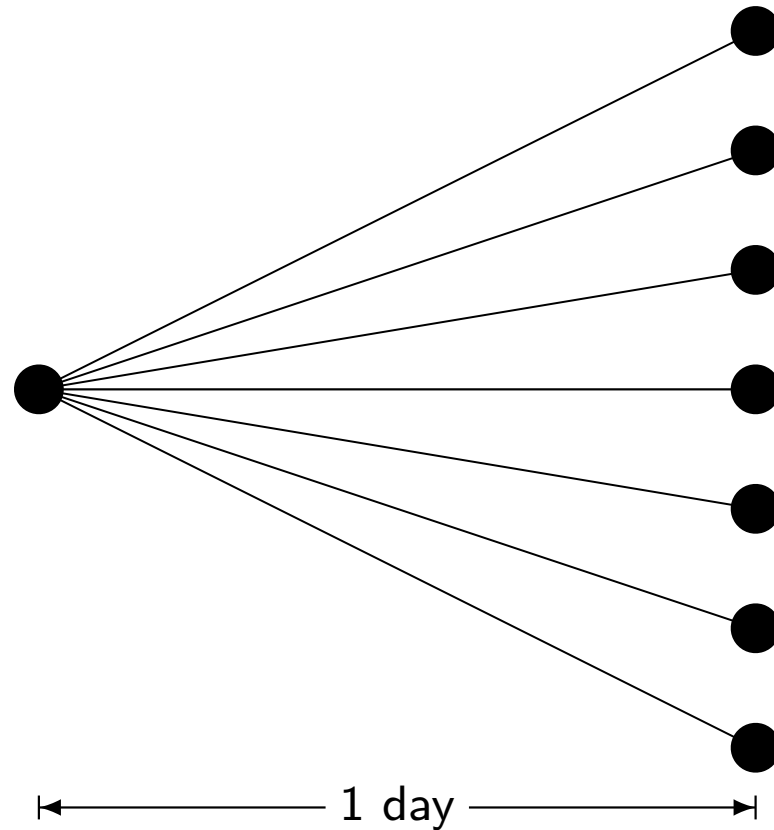


Daily Monitoring

- Almost all barrier options monitor the barrier only for daily closing prices.
- If so, only nodes at the end of a day need to check for the barrier condition.
- We can even remove intraday nodes to create a multinomial tree.
 - A node is then followed by $d + 1$ nodes if each day is partitioned into d periods.
- Does this saves time or space?^a

^aContributed by Ms. Chen, Tzu-Chun (R94922003) and others on April 12, 2006.

A Heptanomial Tree (6 Periods Per Day)



Foreign Currencies

- S denotes the spot exchange rate in domestic/foreign terms.
- σ denotes the volatility of the exchange rate.
- r denotes the domestic interest rate.
- \hat{r} denotes the foreign interest rate.
- A foreign currency is analogous to a stock paying a known dividend yield.
 - Foreign currencies pay a “continuous dividend yield” equal to \hat{r} in the foreign currency.

Foreign Exchange Options

- Foreign exchange options are settled via delivery of the underlying currency.
- A primary use of foreign exchange (or forex) options is to hedge currency risk.
- Consider a U.S. company expecting to receive 100 million Japanese yen in March 2000.
- Those 100 million Japanese yen will be exchanged for U.S. dollars.

Foreign Exchange Options (continued)

- The contract size for the Japanese yen option is JPY6,250,000.
- The company purchases $100,000,000 / 6,250,000 = 16$ puts on the Japanese yen with a strike price of \$.0088 and an exercise month in March 2000.
- This gives the company the right to sell 100,000,000 Japanese yen for $100,000,000 \times .0088 = 880,000$ U.S. dollars.

Foreign Exchange Options (concluded)

- The formulas derived for stock index options in Eqs. (25) on p. 272 apply with the dividend yield equal to \hat{r} :

$$C = Se^{-\hat{r}\tau} N(x) - Xe^{-r\tau} N(x - \sigma\sqrt{\tau}), \quad (29)$$

$$P = Xe^{-r\tau} N(-x + \sigma\sqrt{\tau}) - Se^{-\hat{r}\tau} N(-x). \quad (29')$$

– Above,

$$x \equiv \frac{\ln(S/X) + (r - \hat{r} + \sigma^2/2) \tau}{\sigma\sqrt{\tau}}.$$

Bar the roads!
Bar the paths!
Wert thou to flee from here, wert thou
to find all the roads of the world,
the way thou seekst
the path to that thou'dst find not[.]
— Richard Wagner (1813–1883), *Parsifal*

Path-Dependent Derivatives

- Let S_0, S_1, \dots, S_n denote the prices of the underlying asset over the life of the option.
- S_0 is the known price at time zero.
- S_n is the price at expiration.
- The standard European call has a terminal value depending only on the last price, $\max(S_n - X, 0)$.
- Its value thus depends only on the underlying asset's terminal price regardless of how it gets there.

Path-Dependent Derivatives (continued)

- Some derivatives are path-dependent in that their terminal payoff depends critically on the path.
- The (arithmetic) average-rate call has this terminal value:

$$\max \left(\frac{1}{n+1} \sum_{i=0}^n S_i - X, 0 \right).$$

- The average-rate put's terminal value is given by

$$\max \left(X - \frac{1}{n+1} \sum_{i=0}^n S_i, 0 \right).$$

Path-Dependent Derivatives (continued)

- Average-rate options are also called Asian options.
- They are very popular.^a
- They are useful hedging tools for firms that will make a stream of purchases over a time period because the costs are likely to be linked to the average price.
- They are mostly European.

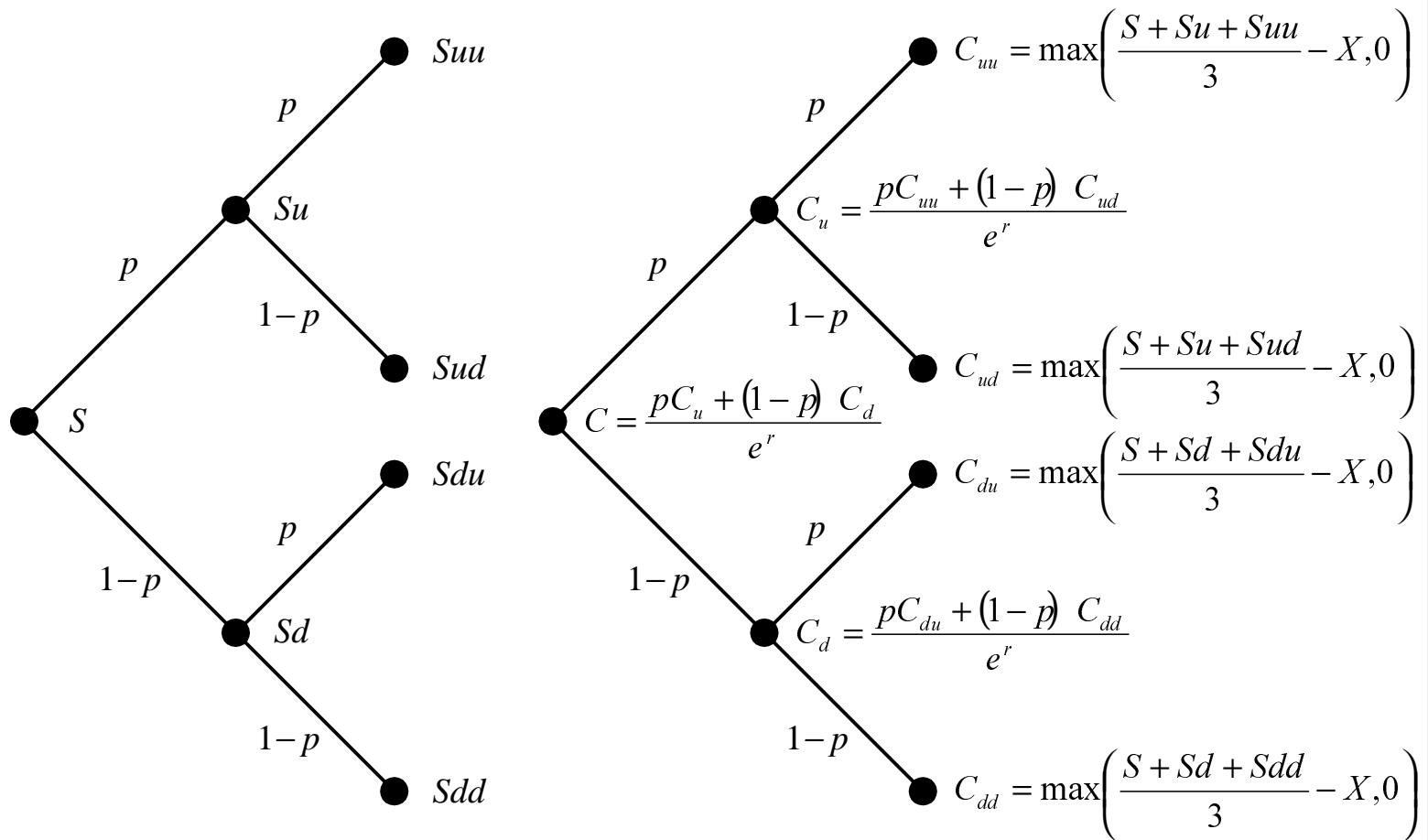
^aAs of the late 1990s, the outstanding volume was in the range of 5–10 billion U.S. dollars according to Nielsen and Sandmann (2003).

Path-Dependent Derivatives (concluded)

- A lookback call option on the minimum has a terminal payoff of $S_n - \min_{0 \leq i \leq n} S_i$.
- A lookback put on the maximum has a terminal payoff of $\max_{0 \leq i \leq n} S_i - S_n$.
- The fixed-strike lookback option provides a payoff of
 - $\max(\max_{0 \leq i \leq n} S_i - X, 0)$ for the call.
 - $\max(X - \min_{0 \leq i \leq n} S_i, 0)$ for the put.
- Lookback calls and puts on the average (instead of a constant X) are called average-strike options.

Average-Rate Options

- Average-rate options are notoriously hard to price.
- The binomial tree for the averages does not combine (see next page).
- A straightforward algorithm enumerates the 2^n price paths for an n -period binomial tree and then averages the payoffs.
- But the complexity is exponential.
- As a result, the Monte Carlo method and approximation algorithms are some of the alternatives left.



States and Their Transitions

- The tuple

$$(i, S, P)$$

captures the state^a for the Asian option.

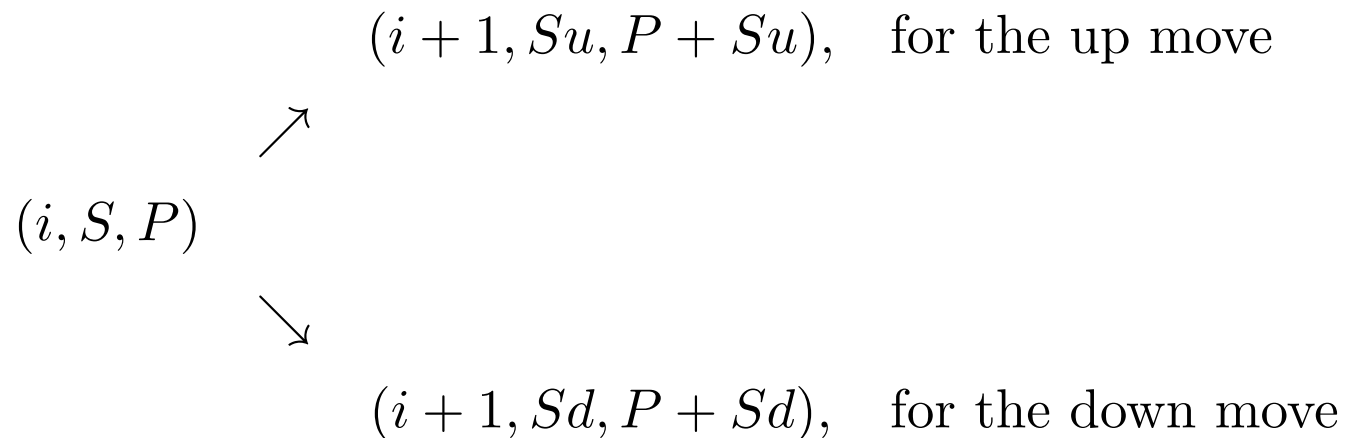
- i : the time.
- S : the prevailing stock price.
- P : the running sum.^b

^aA “sufficient statistic,” if you will.

^bWhat if the average is a moving average?

States and Their Transitions (concluded)

- For the binomial model, the state transition is:



Pricing Some Path-Dependent Options

- Not all path-dependent derivatives are hard to price.
- Barrier options are easy to price.
- When averaging is done *geometrically*, the option payoffs are

$$\begin{aligned} & \max \left((S_0 S_1 \cdots S_n)^{1/(n+1)} - X, 0 \right), \\ & \max \left(X - (S_0 S_1 \cdots S_n)^{1/(n+1)}, 0 \right). \end{aligned}$$

Pricing Some Path-Dependent Options (concluded)

- The limiting analytical solutions are the Black-Scholes formulas.
 - With the volatility set to $\sigma_a \equiv \sigma/\sqrt{3}$.
 - With the dividend yield set to $q_a \equiv (r + q + \sigma^2/6)/2$.
- The formula is therefore

$$C = Se^{-q_a\tau} N(x) - Xe^{-r\tau} N(x - \sigma_a\sqrt{\tau}), \quad (30)$$

$$P = Xe^{-r\tau} N(-x + \sigma_a\sqrt{\tau}) - Se^{-q_a\tau} N(-x), \quad (30')$$

$$- \quad x \equiv \frac{\ln(S/X) + (r - q_a + \sigma_a^2/2)\tau}{\sigma_a\sqrt{\tau}}.$$

An Approximate Formula for Asian Calls^a

$$C = e^{-r\tau} \left[\frac{S}{\tau} \int_0^\tau e^{\mu t + \sigma^2 t/2} N \left(\frac{-\gamma + (\sigma t/\tau)(\tau - t/2)}{\sqrt{\tau/3}} \right) dt - X N \left(\frac{-\gamma}{\sqrt{\tau/3}} \right) \right],$$

where

- $\mu \equiv r - \sigma^2/2$.
- γ is the unique value that satisfies

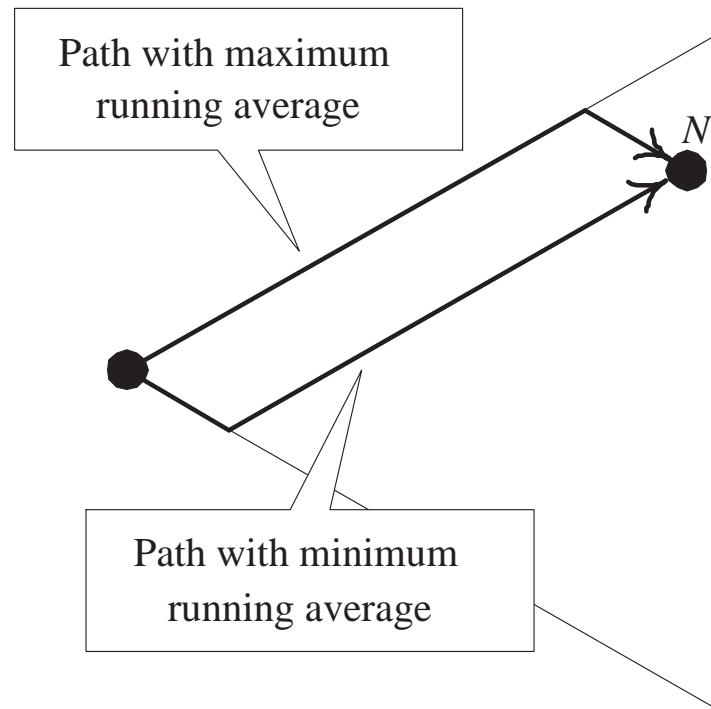
$$\frac{S}{\tau} \int_0^\tau e^{3\gamma\sigma t(\tau-t/2)/\tau^2 + \mu t + \sigma^2[t - (3t^2/\tau^3)(\tau-t/2)^2]/2} dt = X.$$

^aRogers and Shi (1995); Thompson (1999); Chen (R92723061) (2005); Chen (R92723061) and Lyuu (2006).

Approximation Algorithm for Asian Options

- Based on the BOPM.
- Consider a node at time j with the underlying asset price equal to $S_0 u^{j-i} d^i$.
- Name such a node $N(j, i)$.
- The running sum $\sum_{m=0}^j S_m$ at this node has a maximum value of

$$\begin{aligned} & S_0 \overbrace{(1 + u + u^2 + \cdots + u^{j-i} + u^{j-i}d + \cdots + u^{j-i}d^i)}^j \\ &= S_0 \frac{1 - u^{j-i+1}}{1 - u} + S_0 u^{j-i} d \frac{1 - d^i}{1 - d}. \end{aligned}$$



Approximation Algorithm for Asian Options (continued)

- Divide this value by $j + 1$ and call it $A_{\max}(j, i)$.
- Similarly, the running sum has a minimum value of

$$S_0(1 + \overbrace{d + d^2 + \cdots + d^i + d^i u + \cdots + d^i u^{j-i}}^j)$$

$$= S_0 \frac{1 - d^{i+1}}{1 - d} + S_0 d^i u \frac{1 - u^{j-i}}{1 - u}.$$

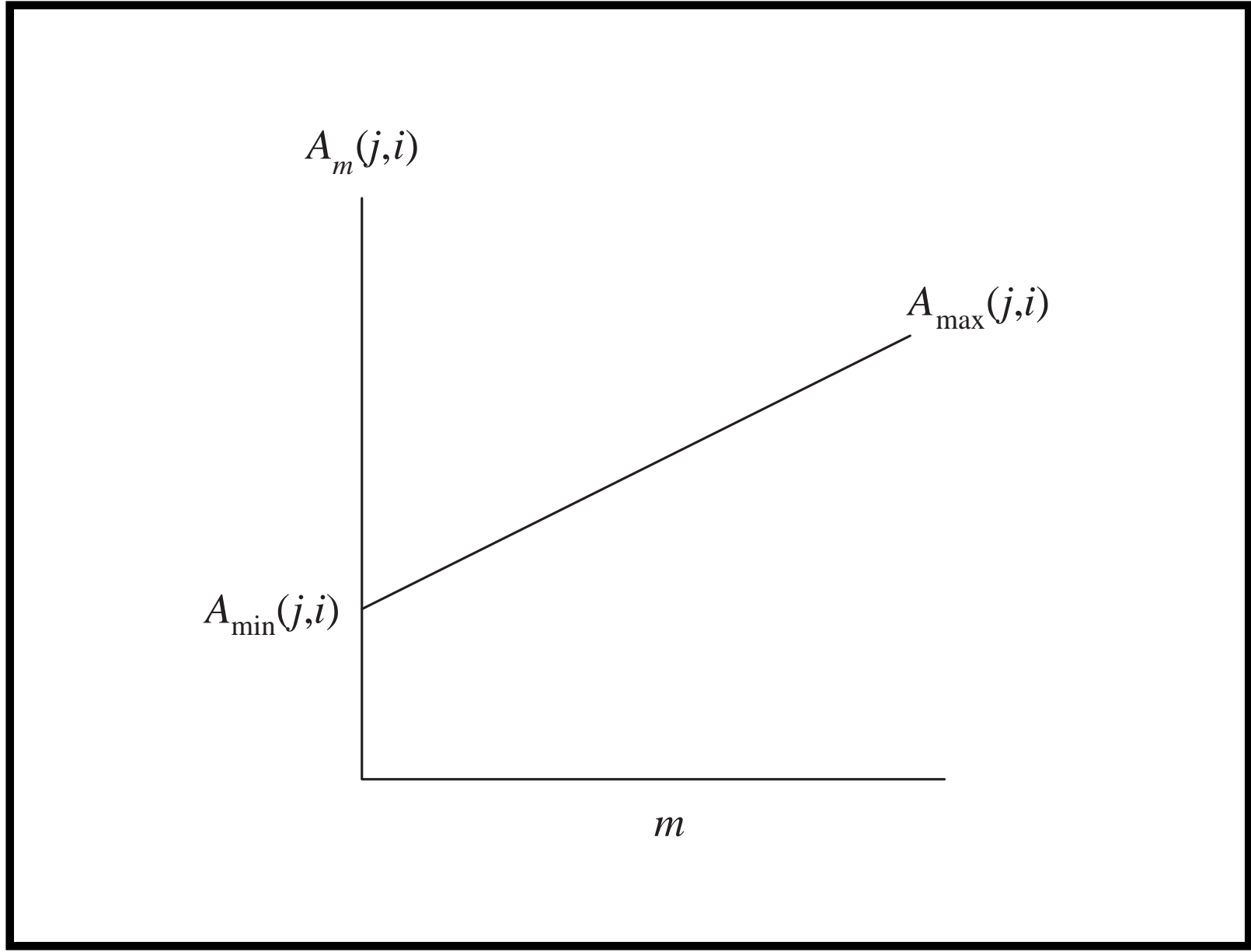
- Divide this value by $j + 1$ and call it $A_{\min}(j, i)$.
- A_{\min} and A_{\max} are running averages.

Approximation Algorithm for Asian Options (continued)

- The possible running averages at $N(j, i)$ are far too many: $\binom{j}{i}$.
 - For example, $\binom{j}{j/2} \approx 2^j \sqrt{2/(\pi j)}$.
- But all must lie between $A_{\min}(j, i)$ and $A_{\max}(j, i)$.
- Pick $k + 1$ equally spaced values in this range and treat them as the true and only running averages:

$$A_m(j, i) \equiv \left(\frac{k - m}{k} \right) A_{\min}(j, i) + \left(\frac{m}{k} \right) A_{\max}(j, i)$$

for $m = 0, 1, \dots, k$.



Approximation Algorithm for Asian Options (continued)

- Such “bucketing” introduces errors, but it works reasonably well in practice.^a
- A better alternative picks values whose logarithms are equally spaced.
- Still other alternatives are possible.
- Generally, k must scale with at least n to show convergence.^b

^aHull and White (1993).

^bDai (R86526008, D8852600), Huang (F83506075), and Lyuu (2002).

Approximation Algorithm for Asian Options (continued)

- Backward induction calculates the option values at each node for the $k + 1$ running averages.
- Suppose the current node is $N(j, i)$ and the running average is a .
- Assume the next node is $N(j + 1, i)$, after an up move.
- As the asset price there is $S_0 u^{j+1-i} d^i$, we seek the option value corresponding to the running average

$$A_u \equiv \frac{(j + 1) a + S_0 u^{j+1-i} d^i}{j + 2}.$$

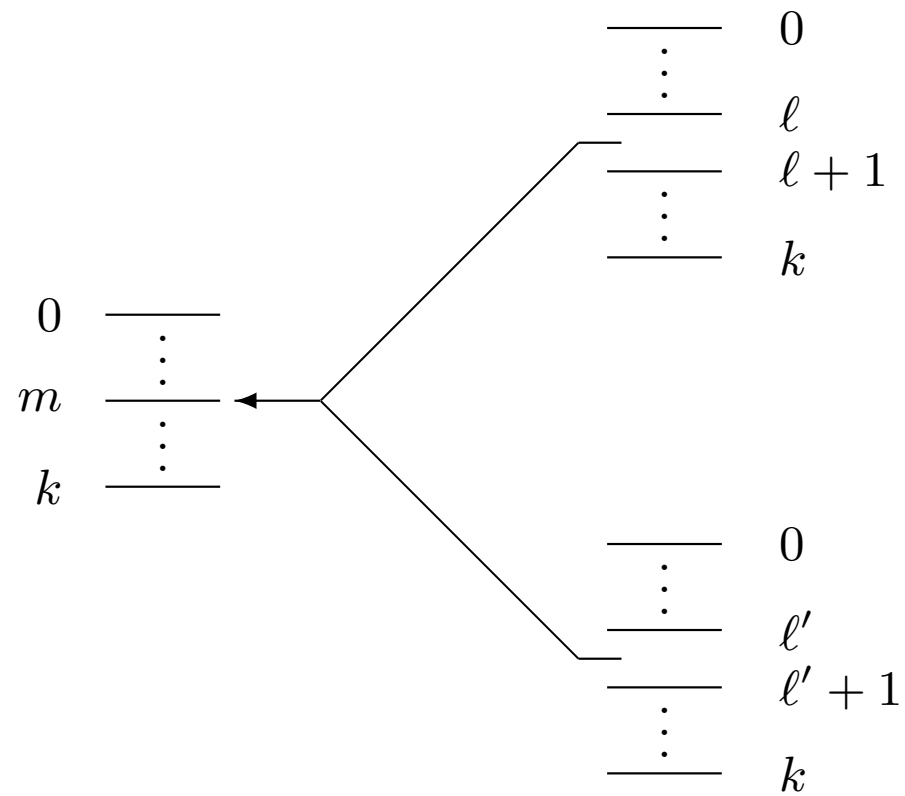
Approximation Algorithm for Asian Options (continued)

- But A_u is not likely to be one of the $k + 1$ running averages at $N(j + 1, i)$!
- Find the 2 running averages that bracket it:

$$A_\ell(j + 1, i) \leq A_u \leq A_{\ell+1}(j + 1, i).$$

- Express A_u as a linearly interpolated value of the two running averages,

$$A_u = x A_\ell(j + 1, i) + (1 - x) A_{\ell+1}(j + 1, i), \quad 0 \leq x \leq 1.$$



Approximation Algorithm for Asian Options (continued)

- Obtain the approximate option value given the running average A_u via

$$C_u \equiv xC_\ell(j+1, i) + (1-x)C_{\ell+1}(j+1, i).$$

- $C_\ell(t, s)$ denotes the option value at node $N(t, s)$ with running average $A_\ell(t, s)$.
- This interpolation introduces the second source of error.

Approximation Algorithm for Asian Options (continued)

- The same steps are repeated for the down node $N(j + 1, i + 1)$ to obtain another approximate option value C_d .
- Finally obtain the option value as

$$[pC_u + (1 - p) C_d] e^{-r\Delta t}.$$

- The running time is $O(kn^2)$.
 - There are $O(n^2)$ nodes.
 - Each node has $O(k)$ buckets.

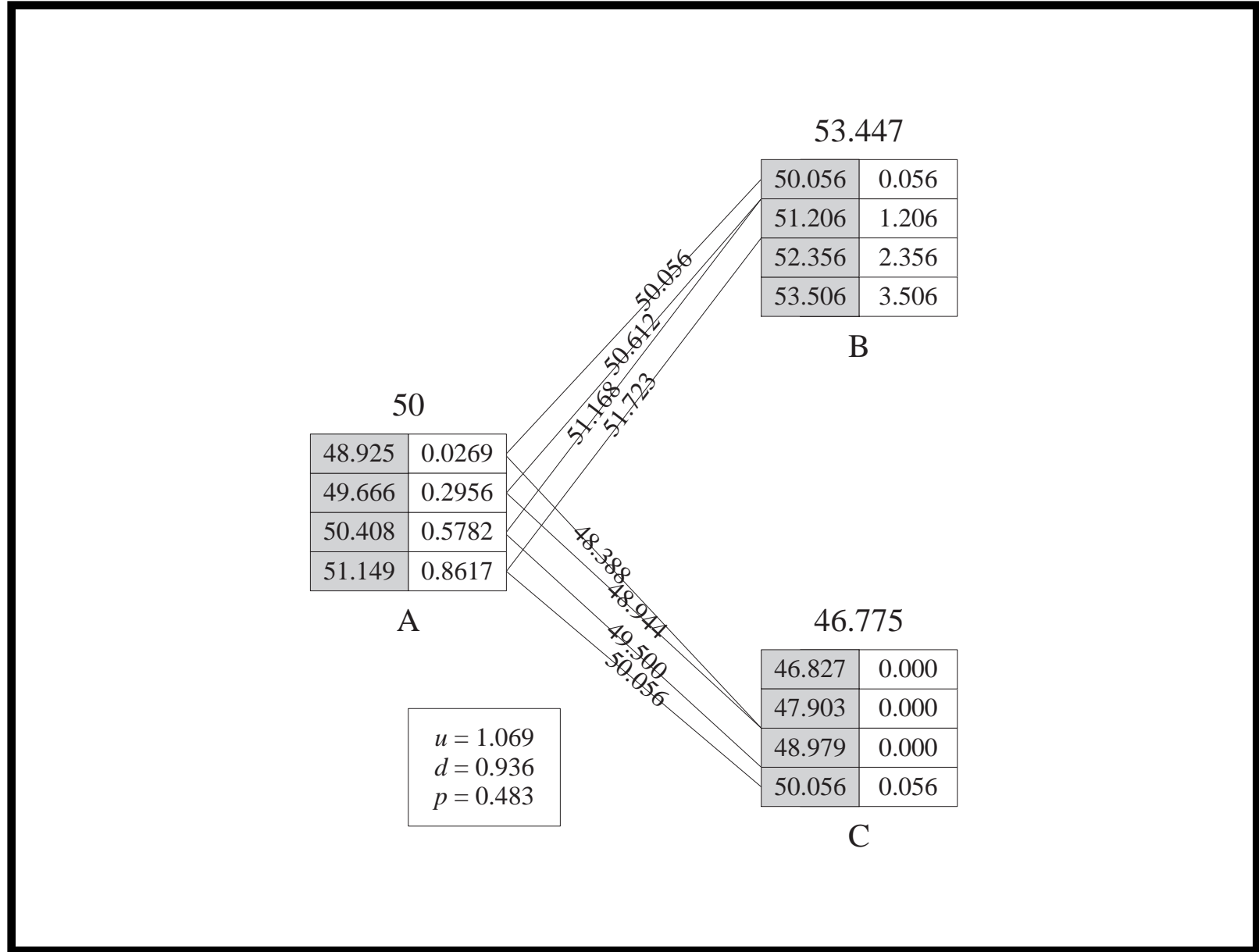
Approximation Algorithm for Asian Options (concluded)

- Arithmetic average-rate options were assumed to be newly issued: no historical average to deal with.
- This problem can be easily addressed (see text).
- How about the Greeks?^a

^aThanks to a lively class discussion on March 31, 2004.

A Numerical Example

- Consider a European arithmetic average-rate call with strike price 50.
- Assume zero interest rate in order to dispense with discounting.
- The minimum running average at node A in the figure on p. 359 is 48.925.
- The maximum running average at node A in the same figure is 51.149.



A Numerical Example (continued)

- Each node picks $k = 3$ for 4 equally spaced running averages.
- The same calculations are done for node A's successor nodes B and C.
- Suppose node A is 2 periods from the root node.
- Consider the up move from node A with running average 49.666.

A Numerical Example (continued)

- Because the stock price at node B is 53.447, the new running average will be

$$\frac{3 \times 49.666 + 53.447}{4} \approx 50.612.$$

- With 50.612 lying between 50.056 and 51.206 at node B, we solve

$$50.612 = x \times 50.056 + (1 - x) \times 51.206$$

to obtain $x \approx 0.517$.

A Numerical Example (continued)

- The option value corresponding to running average 50.056 at node B is 0.056.
- The option values corresponding to running average 51.206 at node B is 1.206.
- Their contribution to the option value corresponding to running average 49.666 at node A is weighted linearly as

$$x \times 0.056 + (1 - x) \times 1.206 \approx 0.611.$$

A Numerical Example (continued)

- Now consider the down move from node A with running average 49.666.
- Because the stock price at node C is 46.775, the new running average will be

$$\frac{3 \times 49.666 + 46.775}{4} \approx 48.944.$$

- With 48.944 lying between 47.903 and 48.979 at node C, we solve

$$48.944 = x \times 47.903 + (1 - x) \times 48.979$$

to obtain $x \approx 0.033$.

A Numerical Example (concluded)

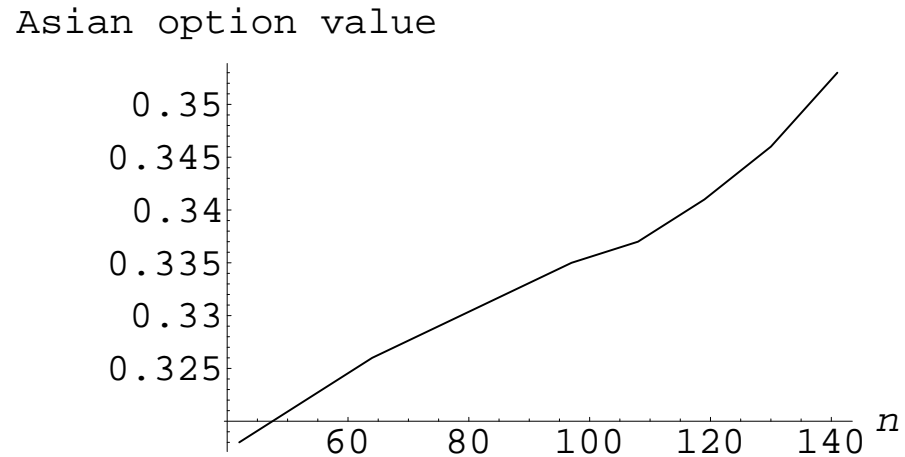
- The option values corresponding to running averages 47.903 and 48.979 at node C are both 0.0.
- Their contribution to the option value corresponding to running average 49.666 at node A is 0.0.
- Finally, the option value corresponding to running average 49.666 at node A equals

$$p \times 0.611 + (1 - p) \times 0.0 \approx 0.2956,$$

where $p = 0.483$.

- The remaining three option values at node A can be computed similarly.

Convergence Behavior of the Approximation Algorithm^a



^aDai (R86526008, D8852600) and Lyuu (2002).

Remarks on Asian Option Pricing

- Asian option pricing is an active research area.
- The above algorithm overestimates the “true” value.^a
- To guarantee convergence, k needs to grow with n .
- There is a convergent approximation algorithm that does away with interpolation with a provable running time of $2^{O(\sqrt{n})}$.^b

^aDai (R86526008, D8852600), Huang (F83506075), and Lyuu (2002).

^bDai (R86526008, D8852600) and Lyuu (2002, 2004).

Remarks on Asian Option Pricing (continued)

- There is an $O(kn^2)$ -time algorithm with an error bound of $O(Xn/k)$ from the naive $O(2^n)$ -time binomial tree algorithm in the case of European Asian options.^a
 - k can be varied for trade-off between time and accuracy.
 - If we pick $k = O(n^2)$, then the error is $O(1/n)$, and the running time is $O(n^4)$.
- In practice, log-linear interpolation works better.

^aAingworth, Motwani, and Oldham (2000).

Remarks on Asian Option Pricing (continued)

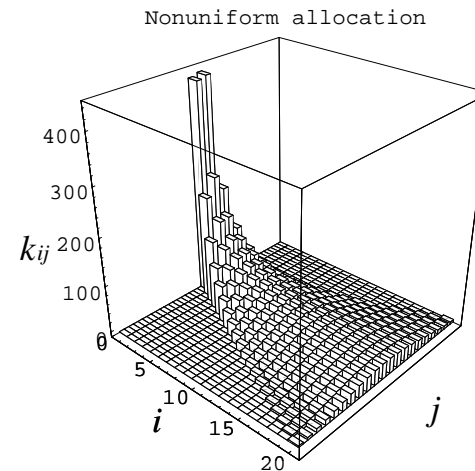
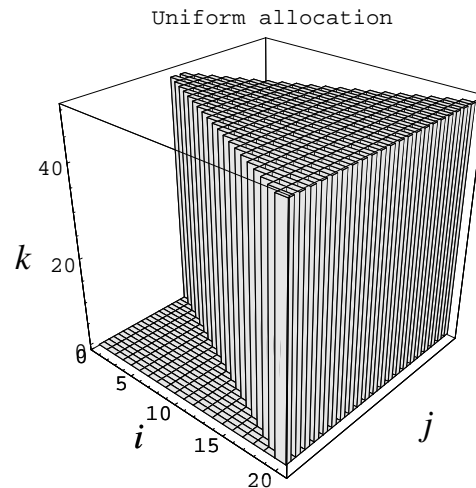
- Another approximation algorithm reduces the error to $O(X\sqrt{n}/k)$.^a
 - It varies the number of buckets per node.
 - If we pick $k = O(n)$, the error is $O(n^{-0.5})$.
 - If we pick $k = O(n^{1.5})$, then the error is $O(1/n)$, and the running time is $O(n^{3.5})$.
- Under “reasonable assumptions,” an $O(n^2)$ -time algorithm with an error bound of $O(1/n)$ exists.^b

^aDai (R86526008, D8852600), Huang (F83506075), and Lyuu (2002).

^bHsu (R7526001) and Lyuu (2004).

Remarks on Asian Option Pricing (concluded)

- The basic idea is a nonuniform allocation of running averages instead of a uniform k .
- It strikes a balance between error and complexity.



A Grand Comparison^a

^aHsu (R7526001) and Lyuu (2004); Zhang (2001,2003); Chen (R92723061) and Lyuu (2006).

X	σ	r	Exact	AA2	AA3	Hsu-Lyu	Chen-Lyu
95	0.05	0.05	7.1777275	7.1777244	7.1777279	7.178812	7.177726
100			2.7161745	2.7161755	2.7161744	2.715613	2.716168
105			0.3372614	0.3372601	0.3372614	0.338863	0.337231
95		0.09	8.8088392	8.8088441	8.8088397	8.808717	8.808839
100			4.3082350	4.3082253	4.3082331	4.309247	4.308231
105			0.9583841	0.9583838	0.9583841	0.960068	0.958331
95		0.15	11.0940944	11.0940964	11.0940943	11.093903	11.094094
100			6.7943550	6.7943510	6.7943553	6.795678	6.794354
105			2.7444531	2.7444538	2.7444531	2.743798	2.744406
90	0.10	0.05	11.9510927	11.9509331	11.9510871	11.951610	11.951076
100			3.6413864	3.6414032	3.6413875	3.642325	3.641344
110			0.3312030	0.3312563	0.3311968	0.331348	0.331074
90		0.09	13.3851974	13.3851165	13.3852048	13.385563	13.385190
100			4.9151167	4.9151388	4.9151177	4.914254	4.915075
110			0.6302713	0.6302538	0.6302717	0.629843	0.630064
90		0.15	15.3987687	15.3988062	15.3987860	15.398885	15.398767
100			7.0277081	7.0276544	7.0277022	7.027385	7.027678
110			1.4136149	1.4136013	1.4136161	1.414953	1.413286

A Grand Comparison (concluded)

X	σ	r	Exact	AA2	AA3	Hsu-Lyuu	Chen-Lyuu
90	0.20	0.05	12.5959916	12.5957894	12.5959304	12.596052	12.595602
100			5.7630881	5.7631987	5.7631187	5.763664	5.762708
110			1.9898945	1.9894855	1.9899382	1.989962	1.989242
90		0.09	13.8314996	13.8307782	13.8313482	13.831604	13.831220
100			6.7773481	6.7775756	6.7773833	6.777748	6.776999
110			2.5462209	2.5459150	2.5462598	2.546397	2.545459
90		0.15	15.6417575	15.6401370	15.6414533	15.641911	15.641598
100			8.4088330	8.4091957	8.4088744	8.408966	8.408519
110			3.5556100	3.5554997	3.5556415	3.556094	3.554687
90	0.30	0.05	13.9538233	13.9555691	13.9540973	13.953937	13.952421
100			7.9456288	7.9459286	7.9458549	7.945918	7.944357
110			4.0717942	4.0702869	4.0720881	4.071945	4.070115
90		0.09	14.9839595	14.9854235	14.9841522	14.984037	14.982782
100			8.8287588	8.8294164	8.8289978	8.829033	8.827548
110			4.6967089	4.6956764	4.6969698	4.696895	4.694902
90		0.15	16.5129113	16.5133090	16.5128376	16.512963	16.512024
100			10.2098305	10.2110681	10.2101058	10.210039	10.208724
110			5.7301225	5.7296982	5.7303567	5.730357	5.728161

Forwards, Futures, Futures Options, Swaps