

Computational Finance



Binomial Trees

Setup and Notation

- Consider a market containing three assets: a risk-free bond with price $B_t = e^{rt}$, a stock S_t , and a (European style) derivative C_t with maturity T and payoff $C_T(S_T)$ that we wish to price.
- Split the time interval $[0, T]$ into N parts of length $\delta t = T/N$ and let $t_i = i\delta t$, $i = 0, \dots, N$, so that $t_0 = 0$ and $t_N = T$.
- Write $\{B_i, S_i, C_i, i = 0, \dots, N\}$ for the asset prices at time $t_i = i\delta t$. E.g., $C_1 \equiv C_{\delta t}$, $C_N \equiv C_T$, and $B_i = e^{r i\delta t}$.
- The stock price S_i either moves up to $S_{i+1}(u)$ or down to $S_{i+1}(d)$. Usually $S_{i+1}(u) = S_i u$ and $S_{i+1}(d) = S_i d$ for fixed u and d , often $u = 1/d$.

The One-Period Case: $N = 1$.

- To find C_0 , construct a replicating portfolio $V_t \equiv \phi S_t + \psi B_t$ in such a way that

$$\begin{aligned} V_T(u) &= \phi S_0 u + \psi B_0 e^{rT} = C(S_0 u) =: c_u, \\ V_T(d) &= \phi S_0 d + \psi B_0 e^{rT} = C(S_0 d) =: c_d. \end{aligned}$$

- Solving for ϕ and ψB_0 yields

$$\phi = \frac{c_u - c_d}{S_0 u - S_0 d}, \quad \psi B_0 = e^{-rT} \left(c_u - \frac{c_u - c_d}{S_0 u - S_0 d} S_0 u \right).$$

- ϕ is known as the *hedge ratio*, or *delta* of the derivative.

- Therefore,

$$\begin{aligned}
 V_0 &= \phi S_0 + \psi B_0 \\
 &= \frac{c_u - c_d}{u - d} + e^{-rT} \left(c_u - \frac{c_u - c_d}{u - d} u \right) \\
 &= e^{-rT} \left(c_u \frac{e^{rT} - d}{u - d} + c_d \frac{u - e^{rT}}{u - d} \right) \\
 &= e^{-rT} (c_u p + c_d [1 - p]) .
 \end{aligned}$$

- In the absence of arbitrage, we must have $C_0 = V_0$, and hence

$$C_0 = e^{-rT} (c_u p + c_d [1 - p]) .$$

- Interpretation: $p \in [0, 1]$, so p is a probability and C_0 is an expectation.
- p and $1 - p$ are known as *risk-neutral* probabilities. We collect these in the *risk-neutral probability measure* \mathbb{Q} , so that $\mathbb{Q}[u] = 1 - \mathbb{Q}[d] = p$.
- We write

$$C_0 = e^{-rT} \mathbb{E}^{\mathbb{Q}}[C_T] = e^{-rT} (c_u p + c_d [1 - p]).$$

- The probabilities are called risk-neutral because if these were the true probabilities, then all assets would earn the risk-free rate. E.g., you should verify that

$$\mathbb{E}^{\mathbb{Q}}[S_T] = S_0 e^{rT}.$$

- Note that we do *not* assume that $p = \mathbb{P}[u]$. The actual probability $\mathbb{P}[u]$ is *irrelevant* for the value C_0 of the derivative (as long as it is not zero or one).

The N -Period Case

- Next, consider a two-period model ($N = 2$):

$$t = 0$$

$$i = 0$$

$$t = \delta t$$

$$i = 1$$

$$t = T = 2\delta t$$

$$i = N = 2$$

$$S_0$$



$$S_0u$$

$$S_0d$$

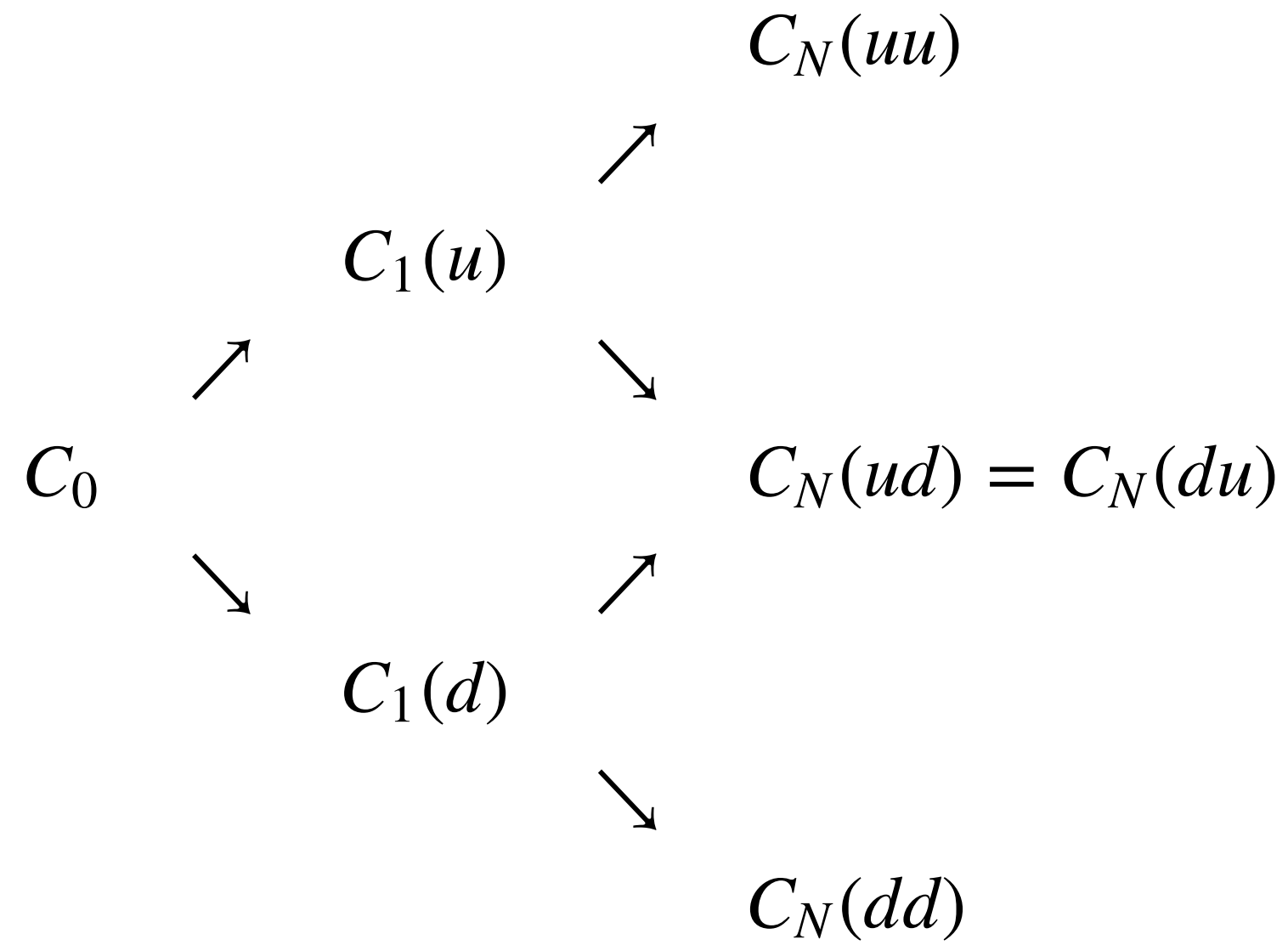


$$S_0uu$$

$$S_0ud = S_0du$$

$$S_0dd$$

- This stock price tree is *recombinant*: an up move followed by a down move leads to the same value as a down move followed by an up move. This is a consequence of u and d being fixed and independent of the price.
- Advantage: the number of nodes remains manageable ($N + 1$ at the N th step, rather than 2^N).
- This leads to a derivative price tree that is also recombinant. Given a recombinant stock price tree, this follows from the fact that C_N only depends on S_N .
- Path-dependent derivatives where $C_N = C(S_i, i \leq N)$ may lead to non-recombinant trees.



- Only the payoffs $C_N(uu)$, $C_N(ud)$ and $C_N(dd)$ are known, and we wish to obtain C_0 , $C_1(u)$ and $C_1(d)$.
- At time $t = \delta t$ (after one step), we know whether the stock has gone up or down.
- If it has gone up, then only the branch from $C_1(u)$ to $C_N(uu)$ or $C_N(ud)$ is relevant.
- Since this is just a binary model, we can price $C_1(u)$ (and $C_1(d)$) by no-arbitrage:

$$C_1(u) = e^{-r \delta t} [C_N(uu)p + C_N(ud)(1 - p)] = e^{-r \delta t} \mathbb{E}^{\mathbb{Q}} [C_N | S_1 = S_0 u],$$

$$C_1(d) = e^{-r \delta t} [C_N(du)p + C_N(dd)(1 - p)] = e^{-r \delta t} \mathbb{E}^{\mathbb{Q}} [C_N | S_1 = S_0 d].$$

- Recall that $p = \frac{e^{r \delta t} - d}{u - d}$; in general the risk-neutral probability might depend on S_1 , but in this case it doesn't, because r , u and d are the same at each step.

- The values $C_1(u)$ and $C_1(d)$ are the market prices (under the no-arbitrage condition), so the derivative can be sold at this price at time $t = \delta t$, depending on whether the stock goes up or down.
- Therefore, at time $t = 0$ we know that the two possible payoffs in the next period are $C_1(u)$ and $C_1(d)$, and so

$$\begin{aligned}
 C_0 &= e^{-r \delta t} [C_1(u)p + C_1(d)(1 - p)] \\
 &= e^{-rT} [C_N(uu)p^2 + C_N(ud)[p(1 - p) + (1 - p)p] \\
 &\quad + C_N(dd)(1 - p)^2] \\
 &= e^{-rT} \mathbb{E}^{\mathbb{Q}} [C_N].
 \end{aligned}$$

- In the N -period case, denote by \mathcal{F}_t the information at time t , i.e., whether the stock went up or down at each $s \leq t$. Then, at each step in the tree,

$$C_t = e^{-r\delta t} \mathbb{E}^{\mathbb{Q}}[C_{t+\delta t} | \mathcal{F}_t].$$

- Starting at C_T , this can be solved backwards until one arrives at the price at $t = 0$.
- At every step in the tree, we have that

$$C_t = e^{-r(T-t)} \mathbb{E}^{\mathbb{Q}}[C_T | \mathcal{F}_t],$$

and in particular

$$C_0 = e^{-rT} \mathbb{E}^{\mathbb{Q}}[C_T].$$

- This is known as the *risk neutral pricing formula*: the price of an attainable European claim equals the expected discounted payoff, but where expectations are under a set of risk-neutral probabilities \mathbb{Q} .

- It is worth noting that the hedging strategy is dynamic: let ϕ_{i+1} and ψ_{i+1} denote the number of shares and cash bonds held from t_i till t_{i+1} .

- The single-period binary model implies

$$\phi_{i+1} = \frac{C_{i+1}(u) - C_{i+1}(d)}{S_{i+1}(u) - S_{i+1}(d)}.$$

- Between t_i and t_{i+1} , the value changes from V_i to $\phi_{i+1}S_{i+1} + \psi_{i+1}B_{i+1}$, after which rebalancing occurs.
- The strategy is *replicating*: after N steps, the value is $V_N = \phi_N S_N + \psi_N B_N = C_N$.

- It can also be verified to be *self-financing*:

$$V_i = \phi_i S_i + \psi_i B_i = \phi_{i+1} S_i + \psi_{i+1} B_i,$$

which may be rewritten as

$$V_{i+1} - V_i = \phi_{i+1}(S_{i+1} - S_i) + \psi_{i+1}(B_{i+1} - B_i).$$

- Thus, a dynamic strategy allows us to hedge against more than two states at time T with only two assets.

Martingales and the FTAP

- A sequence of random variables such as $\{S_i\}_{i \geq 0}$ is called a *stochastic process*.
- Observe that under \mathbb{Q} ,

$$\mathbb{E}^{\mathbb{Q}} [S_{i+1} | \mathcal{F}_i] = S_i (up + d(1 - p)) = S_i e^{r\delta t}.$$

- Define the *discounted stock price process* $\tilde{S}_i = S_i e^{-ir\delta t}$. Then

$$\mathbb{E}^{\mathbb{Q}} [\tilde{S}_{i+1} | \mathcal{F}_i] = S_i e^{r\delta t} e^{-(i+1)r\delta t} = S_i e^{-ir\delta t} = \tilde{S}_i.$$

This is the defining property of a *martingale*. Hence, the risk-neutral measure is also called a *martingale measure*.

- \mathbb{Q} and \mathbb{P} are *equivalent* if $\mathbb{Q}[A] = 0 \iff \mathbb{P}[A] = 0$.
- *Fundamental Theorem of Asset Pricing*: if (and only if) the market is arbitrage free, then there exists an equivalent martingale measure \mathbb{Q} under which discounted stock prices are martingales, and the risk neutral pricing formula holds. \mathbb{Q} is unique if the market is complete.

Tree Calibration

- We are given S_0 , T (measured in years), and the function $C_T = C(S_T)$; for a European call, $C(S_T) = \max \{ (S_T - K), 0 \}$.
- We have to choose the number N of steps, and hence $\delta t = T/N$. This involves a trade-off between computational burden and accuracy.
- $r = \log(1 + R)$, where R is the current value (per annum) of a suitable risk-free interest rate (e.g. LIBOR) over the holding period of the option.
- u and d are chosen to match the stock price volatility: under \mathbb{Q} ,

$$R_{i+1} \equiv \log(S_{i+1}/S_i) = \begin{cases} \log u & \text{with probability } p, \\ \log d = -\log u & \text{with probability } 1 - p. \end{cases}$$

- Thus,

$$\mathbb{E}^{\mathbb{Q}}[R_{i+1}] = (2p - 1) \log u, \quad \text{and}$$

$$\sigma^2 \delta t := \text{var}^{\mathbb{Q}}(R_{i+1}) = (\log u)^2 [1 - (2p - 1)^2] \approx (\log u)^2.$$

- Hence we choose

$$u = e^{\sigma \sqrt{\delta t}}, \quad d = 1/u = e^{-\sigma \sqrt{\delta t}}.$$

- Possible estimates for σ :

- Annualized historical volatility (see last week):

$$\sigma = \sqrt{252} \sigma_{t,HIST}$$

- Implied volatility: the value of σ that equates model price and market price (see later).

Binomial Trees in Python

- We will look at several Python implementations and compare their speed.
- The first implementation is a "loopy" version that could be written in a similar way in most imperative programming languages.

```

In [1]: import numpy as np
def calltree(S0, K, T, r, sigma, N):
    """
    European call price based on an N-step binomial tree.
    """
    deltaT = T/float(N)
    u = np.exp(sigma * np.sqrt(deltaT))
    d = 1/u
    p = (np.exp(r*deltaT) - d)/(u-d)
    C = np.zeros((N+1, N+1))
    S = np.zeros((N+1, N+1))
    piu = np.exp(-r*deltaT)*p
    pid = np.exp(-r*deltaT)*(1-p)
    for i in xrange(N+1):
        for j in xrange(i, N+1):
            S[i, j] = S0 * u**j * d**(2*i) #or S0 * u**(j-i) * d**(i)
    for i in xrange(N+1):
        C[i, N] = max(0, S[i, N]-K)
    for j in xrange(N-1, -1, -1):
        for i in xrange(j+1):
            C[i, j] = piu * C[i, j+1] + pid * C[i+1, j+1]
    return C[0, 0]

```

- Let's see if it works:

```
In [2]: S0=11.; K=10.; T=3/12.; r=.02; sigma=.3; N=500;  
calltree(S0, K, T, r, sigma, N)
```

```
Out[2]: 1.2857395761264745
```

- Great. Now let's look at the speed:

```
In [3]: %timeit calltree(S0, K, T, r, sigma, N) #ipython magic for timing things.  
10 loops, best of 3: 162 ms per loop
```

- Loops tend to be slow in Python. It is often preferable to write code in a *vectorized* style.
- This means calling NumPy ufuncs on entire vectors of data, so that the looping happens inside NumPy, i.e., in compiled C code (which means it's fast).

```

In [4]: def calltree_numpy(S0, K, T, r, sigma, N):
        """
        European call price based on an N-step binomial tree.
        """
        deltaT = T/float(N)
        u = np.exp(sigma * np.sqrt(deltaT))
        d = 1/u
        p = (np.exp(r*deltaT) - d)/(u-d)
        piu = np.exp(-r*deltaT)*p
        pid = np.exp(-r*deltaT)*(1-p)
        C = np.zeros((N+1, N+1))
        S = S0 * u**np.arange(N+1) * d**(2*np.arange(N+1)[: , np.newaxis])
        S = np.triu(S) #Keep only the upper triangular part.
        C[:, N] = np.maximum(0, S[:, N]-K) #Note: np.maximum in place of max.
        for j in xrange(N-1, -1, -1):
            C[:, j+1, j] = piu * C[:, j+1, j+1] + pid * C[1:j+2, j+1]
        return C[0, 0]

```

- Let's verify that both implementations give the same answer.
- We'll use NumPy's `allclose` function, which tests if all elements of two arrays are 'close' to one another (hence avoiding floating point precision issues).

```
In [5]: np.allclose(calltree(S0, K, T, r, sigma, N), calltree_numpy(S0, K, T, r, sigma, N))
```

```
Out[5]: True
```

- Now let's time it:

```
In [6]: %timeit calltree_numpy(S0, K, T, r, sigma, N)
```

```
100 loops, best of 3: 4.39 ms per loop
```

- A third option is to use Numba ([user guide](#)).
- Numba implements a *just in time compiler*. It can compile certain (array-heavy) code to native machine code.
- If Numba is able to compile your code, then the speed is often comparable to C.
- All we need to do is import the package, and then add a *decorator* to our function.
- Other than that, the code is exactly the same as our first attempt.

```

In [7]: from numba import jit
        @jit(nopython=True) #Throw an error if the function cannot be compiled.
        def calltree_numba(S0, K, T, r, sigma, N):
            """
            European call price based on an N-step binomial tree.
            """
            deltaT = T/float(N)
            u = np.exp(sigma * np.sqrt(deltaT))
            d = 1/u
            p = (np.exp(r*deltaT) - d)/(u-d)
            C = np.zeros((N+1, N+1))
            S = np.zeros((N+1, N+1))
            piu = np.exp(-r*deltaT)*p
            pid = np.exp(-r*deltaT)*(1-p)
            for i in xrange(N+1):
                for j in xrange(i, N+1):
                    S[i, j] = S0 * u**j * d**(2*i)
            for i in xrange(N+1):
                C[i, N] = max(0, S[i, N]-K)
            for j in xrange(N-1, -1, -1):
                for i in xrange(j+1):
                    C[i, j] = piu * C[i, j+1] + pid * C[i+1, j+1]
            return C[0, 0]

```

- Check that it gives the right answer:

```
In [8]: np.allclose(calltree(S0, K, T, r, sigma, N), calltree_numba(S0, K, T, r, sigma, N))
```

```
Out[8]: True
```

- The moment of truth:

```
In [9]: %timeit calltree_numba(S0, K, T, r, sigma, N)
```

```
100 loops, best of 3: 4.94 ms per loop
```


- Not bad at all. We essentially match our NumPy implementation.
- There's one more thing we might try: what if we JIT-compile the vectorized version?
- Instead of writing out the whole function again, we'll use an alternative way to invoke the JIT compiler:

```
In [10]: calltree_numpy_numba=jit(calltree_numpy)
         np.allclose(calltree(S0, K, T, r, sigma, N), calltree_numpy_numba(S0, K, T, r, sigma, N))
```

```
Out[10]: True
```

```
In [11]: %timeit calltree_numpy_numba(S0, K, T, r, sigma, N)
         1000 loops, best of 3: 1.67 ms per loop
```

- Wow, can't hate that.
- Looking at the absolute timings, the improvements may seem small, but keep in mind that you may need to call these functions many many times.
- Other tools for compiling Python to native code include [Cython](#) and [Pythran](#).

A Closed Form for European Options

- The price of a European option

$$C_0 = e^{-rT} \mathbb{E}^{\mathbb{Q}} [\max(S_T - K, 0)]$$

depends only on S_T , so there is no need to use a tree explicitly to evaluate it.

- Let k denote the number of up moves of the stock, so that $N - k$ is the number of down moves. Then

$$S_T = S_0 u^k d^{N-k} = S_0 u^{2k-N},$$

where under \mathbb{Q} , $k \sim \text{Bin}(N, p)$, with pmf $f(k; N, p) = \binom{N}{k} p^k (1 - p)^{N-k}$. Thus

$$C_0 = e^{-rT} \sum_{k=0}^N f(k; N, p) \max(S_0 u^k d^{N-k} - K, 0).$$

- Let a denote the minimum number of up moves so that $S_T > K$, i.e., the smallest integer greater than $N/2 + \log(K/S_0)/(2 \log u)$. Then

$$C_0 = e^{-rT} \sum_{k=a}^N f(k; N, p) [S_0 u^k d^{N-k} - K] .$$

- The second term is $[1 - F(a - 1; N, p)]e^{-rT} K = \bar{F}(a - 1; N, p)e^{-rT} K$, where F is the binomial cdf and \bar{F} is the survivor function.
- Let $p_* = e^{-r\delta t} p u$. The first term is

$$e^{-rT} S_0 \sum_{k=a}^N \binom{N}{k} p^k (1 - p)^{N-k} u^k d^{N-k} = S_0 \sum_{k=a}^N \binom{N}{k} p_*^k (1 - p_*)^{N-k} .$$

- Putting things together,

$$\begin{aligned} C_0 &= S_0 \bar{F}(a - 1; N, p_*) - \bar{F}(a - 1; N, p) e^{-rT} K \\ &= S_0 \mathbb{Q}^*(S_T > K) - \mathbb{Q}(S_T > K) e^{-rT} K \end{aligned}$$

- You will be implementing this in a homework exercise.

The Black-Scholes Formula as Continuous Time Limit

- Let's consider what happens if we let $N \rightarrow \infty$
- A first-order Taylor expansion, together with l'Hopital's rule, can be used to show that, for small δt ,

$$p \approx \frac{1}{2} \left(1 + \sqrt{\delta t} \frac{r - \frac{1}{2}\sigma^2}{\sigma} \right).$$

- Similarly,

$$p^* \approx \frac{1}{2} \left(1 + \sqrt{\delta t} \frac{r + \frac{1}{2}\sigma^2}{\sigma} \right).$$

- Next, Let $X_T \equiv \log S_T$. Then, because R_i is either $\log u$ or $\log d = -\log u$,

$$X_T = \log S_0 + \sum_{i=1}^N R_i = \log S_0 + \sigma \sqrt{\delta t} (2k - N).$$

- As $k \sim \text{Bin}(N, p)$, we have $\mathbb{E}^{\mathbb{Q}}[k] = Np$ and $\text{var}^{\mathbb{Q}}[k] = Np(1 - p)$.
- Thus,

$$\mathbb{E}^{\mathbb{Q}}[X_T] = \log S_0 + \sigma \sqrt{\delta t} N(2p - 1) \rightarrow \log S_0 + (r - \frac{1}{2}\sigma^2)T$$

$$\text{Var}^{\mathbb{Q}}[X_T] = \sigma^2 \delta t 4Np(1 - p) \rightarrow \sigma^2 T.$$

- Finally, as $N \rightarrow \infty$, the distribution of X_T tends to a normal. This follows from the *central limit theorem* and the fact that X_T is the sum of N i.i.d. terms.

- Thus, as $N \rightarrow \infty$,

$$\begin{aligned}\mathbb{Q}(S_T > K) &= \mathbb{Q}(X_T > \log K) = \mathbb{Q}\left(\frac{X_T - \mathbb{E}^{\mathbb{Q}}[X_T]}{\sqrt{\text{Var}^{\mathbb{Q}}[X_T]}} > \frac{\log K - \mathbb{E}^{\mathbb{Q}}[X_T]}{\sqrt{\text{Var}^{\mathbb{Q}}[X_T]}}\right) \\ &= 1 - \Phi\left(\frac{\log K - \mathbb{E}^{\mathbb{Q}}[X_T]}{\sqrt{\text{Var}^{\mathbb{Q}}[X_T]}}\right) =: 1 - \Phi(-d_2) = \Phi(d_2), \text{ where} \\ d_2 &\equiv \frac{\mathbb{E}^{\mathbb{Q}}[X_T] - \log K}{\sqrt{\text{Var}^{\mathbb{Q}}[X_T]}} = \frac{\log(S_0/K) + (r - \frac{1}{2}\sigma^2)T}{\sigma\sqrt{T}}.\end{aligned}$$

- The same argument can be used to show that as $N \rightarrow \infty$, $\mathbb{Q}^*(S_T > K) = \Phi(d_1)$, where

$$d_1 \equiv d_2 + \sigma\sqrt{T} = \frac{\log(S_0/K) + (r + \frac{1}{2}\sigma^2)T}{\sigma\sqrt{T}}.$$

- In summary, we have derived the *Black-Scholes formula*

$$\begin{aligned} C_0 &= S_0\Phi(d_1) - e^{-rT}K\Phi(d_2) \\ &=: BS(S_0, K, T, r, \sigma). \end{aligned}$$

- Implementation in Python:

```
In [12]: from scipy.stats import norm
def blackscholes(S0, K, T, r, sigma):
    """
    Price of a European call in the Black-Scholes model.
    """
    d1 = (np.log(S0)-np.log(K)+(r+sigma**2/2)*T)/(sigma*np.sqrt(T))
    d2 = d1-sigma*np.sqrt(T)
    return S0*norm.cdf(d1)-np.exp(-r*T)*K*norm.cdf(d2)
```

```
In [13]: calltree(S0, K, T, r, sigma, 500), blackscholes(S0, K, T, r, sigma)
```

```
Out[13]: (1.2857395761264745, 1.2858368491569285)
```

- Note that as written, the function can operate on arrays of strikes:

```
In [14]: Ks = np.linspace(8, 10, 5)
blackscholes(S0, Ks, T, r, sigma)
```

```
Out[14]: array([ 3.04764278,  2.56561793,  2.10292676,  1.67202011,  1.28583685])
```

American Options

- Unlike a European call, an American call with price C_t^{Am} can be exercised at any time before it matures. When exercised at $t \leq T$, it pays $\max(S_t - K, 0)$. Hence the call will be exercised early if at time t , $S_t - K > C_t^{Am}$.
- Recall put-call parity: $C_t - P_t = S_t - e^{-r(T-t)} K$, which implies (for $r > 0$)
$$C_t \geq S_t - e^{-r(T-t)} K \geq S_t - K,$$
$$P_t \geq K e^{-r(T-t)} - S_t.$$
- As $C_t^{Am} \geq C_t$, an American call is therefore never exercised early (in the absence of dividends).
- There is no closed-form expression for the price of an American put option, so numerical methods are needed. Binomial trees are a popular choice.

- This works as follows:
 - At step N , the price of the put is $P_N^{Am} = \max(K - S_N, 0)$, just like for a European put.
 - At step $N - 1$, the *continuation value* of the option is $e^{-r\delta t} \mathbb{E}^{\mathbb{Q}}[P_N^{Am}]$. Early exercise yields $K - S_{N-1}$, so

$$P_{N-1}^{Am} = \max(e^{-r\delta t} \mathbb{E}^{\mathbb{Q}}[P_N^{Am} | \mathcal{F}_{N-1}], K - S_{N-1}).$$
 - This is iterated backwards until P_0^{Am} .
- The implementation is part of the homework exercise.

Implied Volatility

- The *implied volatility* (IV, σ_I) of an option is that value of σ which equates the BS model price to the observed market price C_0^{obs} , i.e., it solves
$$C_0^{obs} = BS(S_0, K, T, r, \sigma_I).$$
- If the BS assumptions were correct, then any option traded on the asset should have the same IV, which should in turn equal historical volatility.
- In practice, options with different strikes K and hence *moneyness* K/S_0 have different IVs: *volatility smile* or *smirk/skew*. Also, options with different times to maturity have different IVs: *volatility term structure*.
- These phenomena are evidence of a failure of the assumptions of the Black-Scholes model, most importantly that of a constant volatility σ .

- In practice, the BS formula is used as follows: the implied volatility is computed for options that are already traded in the market, for different strikes and maturities. This leads to the *IV surface*.
- When a new option is issued, the implied volatility corresponding to its strike and time to maturity is determined by interpolation on the surface. The BS formula then gives the corresponding price.
- Mathematically, the IV is the *root* (or *zero*) of the function

$$f(\sigma_I) = BS(S_0, K, T, r, \sigma_I) - C_0^{obs}.$$

- In Python, root finding can be done via SciPy's `brentq` function. In its simplest form, it takes 3 arguments: the unary function $f(\cdot)$, and a lower bound L and upper bound U such that $[L, U]$ contains exactly one root of f .

- [Tehranchi \(2016\)](#) shows that for European calls,

$$-\Phi^{-1}\left(\frac{S_0 - C_0^{obs}}{2 \min(S_0, e^{-rT} K)}\right) \leq \frac{\sqrt{T}}{2} \sigma_I \leq -\Phi^{-1}\left(\frac{S_0 - C_0^{obs}}{S_0 + e^{-rT} K}\right).$$

- It remains to transform our objective function into a unary (single argument) function, through *partial function application* via, e.g., an anonymous function:

```
In [15]: from scipy.optimize import brentq
def impvol(S0, K, T, r, C_obs, Type='call'):
    """Implied Black-Scholes volatility."""
    if Type == 'put': #Convert to call price via parity
        C_obs = C_obs + S0 - np.exp(-r*T)*K
    L = -2*norm.ppf((S0-C_obs)/(2.0*min(S0, np.exp(-r*T)*K)))/np.sqrt(T)
    U = -2*norm.ppf((S0-C_obs)/(S0+np.exp(-r*T)*K))/np.sqrt(T)
    return brentq(lambda s: blackscholes(S0, K, T, r, s)-C_obs, L, U) #Partial application: f(s)=BS(S0, K, T,
```

```
In [16]: C_obs=2. #For illustration.
IV=impvol(S0, K, T, r, C_obs); (IV, blackscholes(S0, K, T, r, IV))
```

```
Out[16]: (0.6802980451017724, 1.9999999999991251)
```

Volatility Smirk, SPX OTM puts/calls expiring 1/2018

