Morgan Stanley

Journal of Applied Corporate Finance

SUMMER 2001 VOLUME 14.2

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REAL OPTIONS PRIMER: A PRACTICAL SYNTHESIS OF CONCEPTS AND VALUATION APPROACHES

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The systematic ability to create shareholder value through capital investment has always been critical to the long-run success of an enterprise. Never before, however, has the uncertainty surrounding investment decisions been greater, as managers increasingly find themselves evaluating requests for capital today in exchange for a stream of almost unknowable net cash flows expected into the future. For some firms, uncertainty arises from a need to make aggressive moves to secure market share in an Internet economy. For others, it results from the opportunities and threats created by rapid technological development and commercialization. In general, market leadership requires calculated risk taking, tempered by the discipline of a quantitative analysis of investment decisions.

Traditionally, investment proposals have been evaluated using the net present value (NPV) approach, wherein discounted future net cash flows are related to the initial investment to assess the likely impact of the project on shareholder wealth. The NPV rule implicitly assumes a "buy and hold" strategy, where the analyst's best guess of future net cash flows attributable to the investment are discounted to present values. The risk of these cash flows is incorporated in the discounting procedure through a risk-adjusted discount rate.

While the traditional NPV criterion does a reasonable job of valuing simple, passively managed projects, it is well established that the criterion does not capture the many ways in which a highly uncertain project might evolve, and the ways in which active managers will influence this evolution.[1] For example, consider the following issue in new product development. A pharmaceutical firm's research and development program recently generated a promising idea for a new pharmaceutical product, and successful Phase II clinical trials of the drug have just been completed. One year of Phase III clinical trials is now required. If the trials lead to FDA approval for an indication with broad market potential, they will be followed by full-scale production. Capital outlays are required to begin the trials, and a much larger expenditure will be required one year from now as mass production is initiated.

*This work has benefited from the helpful comments of Stephen Allen, Fernando Alvarez, Steven Feinstein, Diane Lander, Karen Maccaro, Kirtland Poss, Mark Potter, Gordon Sick, Bob Taggart, many graduate students at the F. W. Olin Graduate School of Management at Babson College, and participants in executive education programs. Any errors or omissions are the sole responsibility of the author.

1. See, for example, Trigeorgis and Mason (1987), Baldwin and Clark (1992), Kulatilaka and Marcus (1992), and Dixit and Pindyk (1995). See Trigeorgis (2001) for a comprehensive review of the academic literature on real options. Full citations for all references appear at the end of the article.

Project cash inflows from full-scale production are highly uncertain, both because they will not be received for more than one year and because they are dependent upon the results of clinical testing. Still, they are estimated as carefully as possible by considering factors such as potential market size, likely market share, and input costs.

The traditional next step in this hypothetical example is the application of the NPV rule. The NPV would be measured as the discounted value of all flows expected for the project: the initial cash outflow for the clinical trials, the plant investment one year hence, and a stream of net cash inflows from full-scale production and distribution. Let's suppose that the NPV of this project is negative, signaling that the drug should not be developed. Were management to reject the project based on a negative NPV, they would be missing a critical feature of the investment opportunity: upon the conclusion of the clinical trials, management has the *right, but not the obligation*, to make additional capital expenditures. That is, if trials reveal an indication with limited market potential, there will be no need to make the large capital expenditures necessary for large-scale production. Standard NPV analysis, however, treats all expected future cash flows as if they will occur, implicitly assuming a passive management strategy. It recognizes no managerial ability to restructure or terminate the project should new information suggest a change in strategy.

An alternative way to look at this investment uses the notion of a call option borrowed from securities markets. A call option is the right, not the obligation, to buy a specified underlying asset at a specified price (the exercise or strike price) and time (the expiration date).[2] In securities markets, the underlying asset is typically a share of stock, although other types of options also are common. Obviously, the option will be exercised only if the value of the underlying asset is above the strike price on the expiration date. Otherwise, the holder of the option will allow it to expire worthless.

How does this apply to our pharma development example? This project is really a series of two consecutive investments, or development stages. Stage One involves non-discretionary cash outflows for Phase III trials; these need to be made to open the door to producing and selling the product. Stage Two can be described as a call option on future cash inflows from the project, where the exercise price is the capital expenditure necessary to initiate full-scale production. This capital expenditure will be made only if the trials are sufficiently successful. The option to make the plant investment in the future is an example of a call option on a real asset, or a real option.

The flexibility inherent in Stage Two is not well addressed with the NPV decision rule. It is more appropriate to evaluate Stage Two using option pricing techniques. In fact, by ignoring the reality that the future capital outlay is subject to managerial discretion, the NPV rule would undervalue this opportunity. Managers, then, may systematically be rejecting product development proposals (and other long-term investment proposals) that really deserve further exploration.

The reality is that effective managers will actively manage their strategic initiatives, including pursuing opportunities created from the initiative, or pulling the plug if warranted. While managers qualitatively recognize the possibilities, they know that sound decisions will be made systematically only if they are subjected to the discipline of a quantitative shareholder value analysis. Most managers recognize the shortcomings of the NPV rule when applied to highly uncertain strategic initiatives, and many are aware that an alternative options-based approach exists. Unfortunately, the shortage of practical guidance on the implementation of a real options analysis leaves a large gap between managerial awareness and implementation. While there is now an excellent body of research on the topic of real options, much of it is so complex that it is not inviting to managers, or so narrow that it creates more questions than it answers. Too many managers remain more intrigued than engaged.

This objective of this paper is to enhance managerial understanding of real options by synthesizing existing knowledge into a simplified, practical approach to their recognition and evaluation. Recent published works by Tim Luehrman (1998) and Aswath Damodaran (2000) have helped to close the understanding gap by illustrating the use of the

2. This defines a *European option*, which can be exercised only on the expiration date. In contrast, an *American option* allows the holder to exercise any time until and including the expiration date.

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Black-Scholes option pricing model to value real options. A recent paper by Lenos Trigeorgis (2001) demonstrates the valuation of real options using a binomial approach. The current paper contributes to the literature by addressing the relationship between the binomial and Black-Scholes approaches, and introducing the mathematical details necessary to implement a real options analysis using either method. By demonstrating the distinctive properties of an option through a binomial approach, together with an illustration of how the binomial model converges to the Black-Scholes model, this paper seeks to help the reader gain an understanding of the essence of both approaches. This paper certainly will not make the reader an expert in real option valuation, and is not intended to replace more detailed books written on the topic.[3] Instead it is intended to be a concise and practical introduction to the basic principles of valuing real options.

The remainder of this paper is organized as follows: Examples of four basic categories of real options—timing, growth, production, and abandonment—are introduced in the second section using a simple binomial framework. That is, each example assumes that there are two possible payoffs to the capital investment project at the end of a year. The examples are used to illustrate the various forms of a real option, and to demonstrate the shortcomings of an NPV analysis where flexibility is present. The third section shows how the restrictive nature of the binomial approach (that is, allowing for only two outcomes) can be overcome by allowing for increasing numbers of binomial trials within the planning period. It describes how, as the number of binomial trials approaches infinity, the binomial model converges to the Black-Scholes Option Pricing Model.[4] While the Black-Scholes model was developed to value options written on securities, the manner in which it can be extended to the valuation of real options is outlined. To illustrate these extensions, an example introduced in section two is re-worked in section three within the Black-Scholes framework. The fourth section addresses the appropriate discount rate to use in a real options analysis, and the fifth section addresses the issue of volatility and the mathematical details of constructing an event tree for a binomial analysis.

THE MANY FACES OF A REAL OPTION

1. A Timing Option: Pharmaceutical Development

Let's flesh out the pharmaceutical example introduced above. Suppose that Phase II clinical trials of this new drug have just been completed, and the firm is about to launch critical Phase III trials. Past experience with similar compounds suggests a 33.0% probability of success to the trials, where success is defined as FDA approval for an indication with broad market potential. Should the trials be successful, the value one year from now of expected cash inflows from that point on under full-scale production is estimated to be \$39 million. Should the trials be unsuccessful (67.0% probability), FDA approval for an application with limited potential will result, and the value in one year of the expected cash inflows is estimated to be \$4.3 million. Full-scale production requires the construction of a new plant with an estimated cost today of \$10 million. If clinical trials require an up-front investment of \$4 million, and the firm's risk-adjusted required rate of return on this project is 20%, should the trials be undertaken?

Managers traditionally would answer this question by computing the NPV of the project. This is quite straightforward since there are only three cash flows: an outflow of \$4 million today for the trials, an outflow of \$10 million today for plant construction, and a probability weighted average of payoffs to be received in one year. The NPV calculation is as follows:

$$\begin{aligned}\text{NPV} &= -\$14 + ([(.330)(\$39.00) + (.670)(\$4.30)]/(1+.20)) \\ &= -\$0.9 \text{ million}\end{aligned} \qquad [1]$$

According to this calculation, this investment will reduce shareholder wealth by approximately \$0.9 million, and should be rejected.

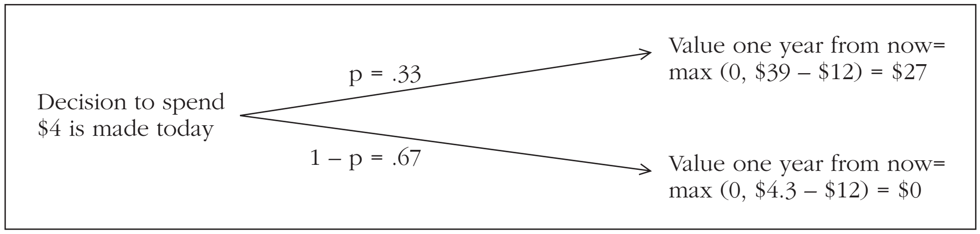
But, wait a minute: the above calculation assumes the plant will be constructed today, before the outcome of the trials is known. Suppose we factor in our ability to choose to make the plant investment. Specifically, suppose the firm estimates that it can construct the same plant for an investment of \$12 million[5] one year from now. Trials would begin

3. See, for example, Copeland and Antikarov (2001), Trigeorgis (1999), or Amram and Kulatilaka (1999).

4. Black and Scholes (1973).

5. This figure is based on the assumption that the cost of the plant will rise during the year at the risk-adjusted rate of return of 20%.

FIGURE 1



today, so the outcome of the trials (successful or unsuccessful) and the estimated present value of future cash inflows ($39 million or $4.3 million) would be known at the time the plant construction would begin. Of course, it would be rational to make the plant investment should the trials be successful, because it clearly makes sense to invest $12 million to realize a value of $39 million. If the trials are not successful, the investment will not be made, because it does not make sense to invest $12 million to realize a value of $4.3 million.

Placing a value on the project from this new point of view is made easier by constructing an "event tree," which is a graphical representation of the possible outcomes of the project and their associated probabilities. For this project, the event tree is shown in Figure 1.

For simplicity, let's assume that the discount rate appropriate for this project remains at 20%. (We will show later that it is not correct to discount option payoffs at a risk-adjusted rate, but making this simplifying assumption here allows us to make progress in understanding how valuations change when they explicitly incorporate operating flexibility.) The value of the project today, modified to reflect the option to delay, is

$$\text{Modified NPV} = -\$4 + ([(.330)(\$27.00) + (.670)(\$0)]/(1 + .20)) = \$3.4 \text{ million} \quad [2]$$

Incorporating managerial discretion (the option to delay plant construction) changes our recommendation: If we have the choice to invest the $12 million only if the outcome of clinical trials is favorable, this project adds over $3 million to shareholder wealth, and the initial $4 million investment is justified.

This provides a good opportunity to point out a distinctive feature of an asset as an option, and it involves the relationship between risk and value. Suppose that we were more uncertain about the success of the clinical trials, and were facing an even wider spread of future outcomes. That is, we would expect something more than $39 million in value if the trials are successful, and something less than $4.3 million in value if trials are unsuccessful. How does this affect the value of our option? The downside is truncated at zero; no matter how poor our results may be, we will realize a value no less than zero, because we simply will not invest. On the other hand, the possibility for greater value on the upside represents a source of additional value, and the option value will rise. In other words, there is a positive relationship between uncertainty and option value, because the option allows us to capture the upside while eliminating the downside.

This example uses simplifying assumptions to illustrate how thinking of a capital investment as an option affects its valuation. While it appears simple to this point, it is important to state that we have abstracted from some implementation details in order to illustrate the essence of options approaches. These details will be addressed in sections four and five, and include the determination of the appropriate discount rate and the measurement and incorporation of risk.

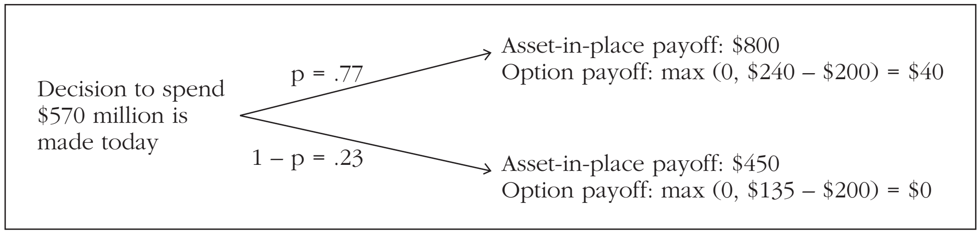
2. A Growth Option: e-commerce

Now that we have developed a basic understanding of the role of flexibility in project selection decisions, let's move on to a slightly more complex example. Suppose you are a member of a small management team seeking venture capital for a promising new business-to-business electronic commerce venture. This is a highly uncertain proposition, but you have a hunch that the possibilities are endless. The first year is critical, because extensive market research indicates that initial client receptivity will largely determine the long-run success of the venture.

The up-front investment, which totals $570 million, includes outlays for warehousing facilities and a technology infrastructure. The realities of

Never before has the uncertainty surrounding investment decisions been greater, as managers increasingly find themselves evaluating requests for capital today in exchange for a stream of almost unknowable net cash flows expected into the future.

FIGURE 2



development cost relative to scale cause you to propose a larger warehouse capacity and more robust technological capabilities than are needed to support initial sales expectations. The benefit of this excess capacity, however, is that it will be more efficient for you to scale up should your product be well received. At initial capacity levels, the firm is expected to generate one year from now a present value of future cash inflows of $800 million with 77% probability or $450 million with 23% probability. The additional capacity would require $200 million in additional investment one year from now, and is expected to increase the present value of cash flows by 30% in each scenario (i.e., an additional $240 million for the favorable outcome, and an additional $135 million for the unfavorable outcome). Standard valuation of the full potential of this project would recognize a cash outflow of $570 million today, an outflow of $200 million one year from now, and values in one year of $1,040 million ($800 + $240) with 77% probability, or $585 million ($450 + $135) with 23% probability. Assuming your backers require a risk-adjusted rate of return of 18% on this venture, the project NPV would be

$$\begin{aligned}\textbf{NPV} &= -\$570 + ([-\$200/(1 + .18)] + [(.77)(\$1040) + \\ &\quad (0.23)(\$585)]/(1 + .18)) \\ &= \$53 \text{ million} \end{aligned} \qquad [3]$$

This figure indicates that the venture is expected to cover expectations of an 18% return, and provide an estimated additional shareholder value of $53 million.

But let's think for a moment about the nature of this investment. It actually can be decomposed into two distinct segments: an "asset-in-place" and a call option. The value of the asset-in-place is determined by the payoffs at the project's original scale (the initial $570 million investment generates either $800 million or $450 million one year from now). There is no flexibility associated with this segment of the investment. The value of the call option, however, should reflect the fact that you have the right, but not the obligation, to call on the additional capacity for $200 million in one year in exchange for the incremental value of either $240 or $135. Standard NPV approaches will properly value the asset-in-place, but will undervalue the option because they fail to recognize the flexibility inherent in this segment of the project. The event tree for this project, shown in Figure 2, reflects the fact that excess capacity will be brought on line only if the value to be received exceeds the $200 million investment, which occurs only in the more favorable state. The value of the project now becomes the following:

$$\begin{aligned}\textbf{Modified NPV} &= -\$570 + ([(.77)(\$800 + \$40) + \\ &\quad (.23)(\$450 + \$0)]/(1 + .18)) \\ &= \$66 \text{ million} \end{aligned} \qquad [4]$$

This result indicates that incorporating flexibility adds over 24% to the project value, and strengthens the case you will present to your venture backers.

The process used here to value this growth option can be used to evaluate other options as well, options more obscure and less restrictive than this simplified example. Consider a staged entry into a market, where an initial commitment made today to "test the waters" may generate significant future opportunities. Alternatively, consider a research and development program, where the results of today's research may yield new products and cash flows never before considered. The point is that, where managers historically have relied on instinct to build in excess capacity, test the waters, or engage in R&D, real option valuation approaches provide a systematic way to evaluate decisions to engage in these activities, and to set guidelines for how much to spend on them.

3. A Production Option: Copper Mines

A third type of option value can be found in operating flexibility, as illustrated in the following

FIGURE 3

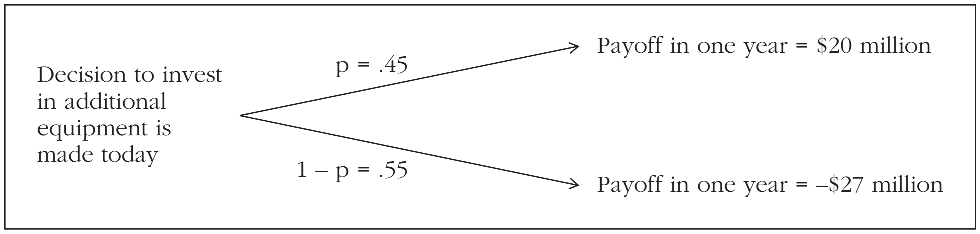
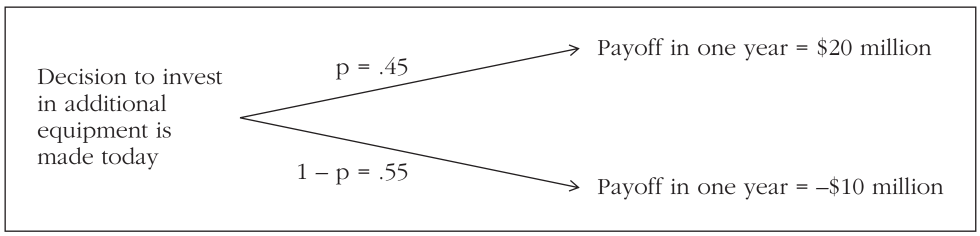


FIGURE 4



example: You are extracting and refining copper ore from a mine in Australia, and the contents of the mine are almost depleted. The remaining contents of the mine, estimated to be sufficient to produce 42 million pounds of refined copper, could be extracted in about one year, but only if you make additional investments to replace equipment. Spot prices of copper on the London Metal Exchange have been quite volatile, and are expected at year-end to be either $1.548 per pound with a 45% probability, or $0.429 per pound with a 55% probability. Variable costs of refinement are expected to be $0.833 per pound, and fixed extraction costs are estimated at $10 million for the year. The risk-adjusted required return for the investment is 15%, and special arrangements with the Australian government allow you to realize tax-free income. What is the most you should invest in additional equipment?

The cash inflow in the favorable state is $20 million, computed as revenue of $65 million (42 million pounds at $1.548 per pound) less variable costs to refine the copper ore of $35 million (42 million pounds at $0.833 per pound) and fixed costs to extract the ore of $10 million. The cash inflow in the unfavorable state is a negative $27 million, computed based on a copper price of $0.429 and costs as in the favorable state. The event tree for the project is shown in Figure 3, and the present value of cash inflows is

$$\textbf{PV (inflows)} = [(.45)(\$20) + (.55)(-\$27)]/(1 + .15) = -\$5 \text{ million} \quad [5]$$

This calculation indicates you should be unwilling to invest any further in this mine. But do you have to refine the copper ore in the unfavorable state? If the price of copper is below the variable cost of production, it is much more sensible to walk away from the investment, and limit your losses on the downside to the unavoidable fixed extraction costs. If we allow for this possibility, the event tree is as shown in Figure 4.

The revised present value of cash inflows

$$\textbf{Modified PV (inflows)} = [(.45)(\$20) + (.55)(-\$10)]/(1 + .15) = \$3 \text{ million} \quad [6]$$

indicates that the option to produce increases the present value of cash inflows from the mine to $3 million, and that any equipment replacement expenditures less than $3 million will create shareholder value.

Many managers, especially in ventures dependent on natural resources, decide on a periodic basis whether or not to produce. While this example is simplified to assume that such a decision is made once, it is straightforward to extend it to incorporate periodic production decisions. This example demonstrates that admitting the possibility of unfavorable outcomes may significantly change the evaluation of a project. By extension, if operating flexibility is present, it is reasonable to incorporate it in the initial evaluation of a project's value.

While the traditional NPV criterion does a reasonable job of valuing simple, passively-managed projects, it does not capture the many ways in which a highly uncertain project might evolve, and the ways in which active managers will influence this evolution.

4. An Abandonment Option: Natural Gas

Our fourth and final example represents another planned response to an unfavorable outcome: the exit strategy. Suppose that you are a planning manager for a natural gas utility, and you are considering a proposal to develop and operate a gas main extension to serve an expanding residential community. The value of the project is driven primarily by the price of natural gas, a highly volatile commodity. The main extension requires \$340 million to construct and will generate future cash inflows that one year from now are expected to have a present value of either \$560 million or \$182 million. These two outcomes are equally likely. A traditional analysis of the main extension, assuming a 16% risk-adjusted discount rate, generates an NPV of

$$\begin{aligned} \text{NPV} &= -\$340 + ([(.5)(\$560 + (.5)(\$182)]/(1 + .16)) \\ &= -\$20 \text{ million,} \end{aligned} \qquad [7]$$

which indicates the project should not be accepted. But suppose that a local distribution company (LDC) has entered into an agreement with you whereby it agrees to purchase the extension from you one year from now for \$250 million, at your option. Obviously, you would only agree to the sale in the less favorable state, and your project valuation becomes

$$\begin{aligned} \text{Modified NPV} &= -\$340 + ([(.5)(\$560) + (.5)(\$250)]/ \\ &\quad (1 + .16)) \\ &= \$9 \text{ million} \end{aligned} \qquad [8]$$

Incorporating the ability to sell the extension causes the project to be acceptable from a shareholder value perspective.

It is not uncommon for far-sighted project advocates to admit the possibility of unfavorable outcomes before a project begins, and many implementation plans include an exit strategy. This example demonstrates that formally incorporating an exit strategy into analyses can cause project acceptance signals to reverse. It may seem counterintuitive that admitting the possibility of unfavorable outcomes could cause unacceptable projects to become acceptable. The reversal occurs where there is a favorable consequence to an unfavorable outcome, which in this case is the ability to sell the extension for more than the value of holding it. This example also demonstrates that there is value in making capital assets adaptable to other uses where possible.

ALLOWING FOR MORE OUTCOMES: THE BLACK-SCHOLES OPTION PRICING MODEL

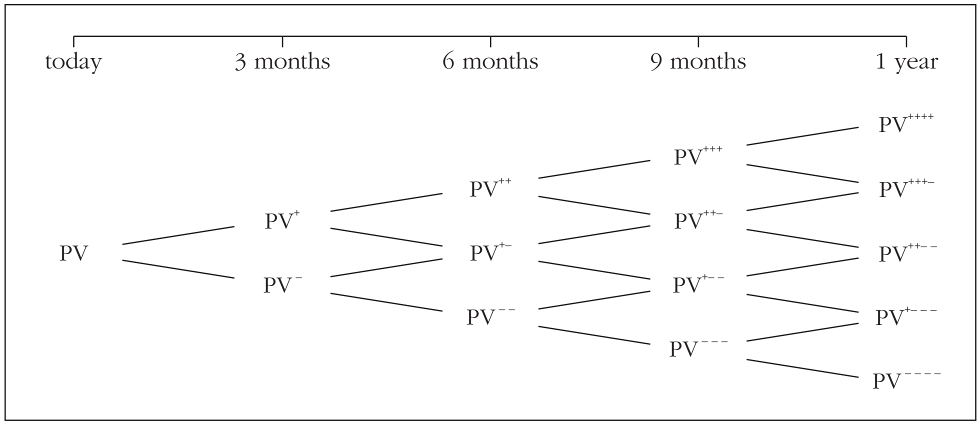
Borrowing from the language of financial markets, we have just valued three call options, which, as we saw earlier, represent the right, but not the obligation, to spend funds in the future to realize cash inflows. In the pharmaceutical timing option example, we held the right to invest \$12 million to construct a plant one year from now. In the case of the growth option, we had the right to invest \$200 million to bring excess capacity on line one year hence. Finally, in the production example, we had the right to incur variable costs of production to exploit a copper mine. We also valued a put option: the right, but not the obligation, to sell an asset in the future for some pre-specified price. In the gas main extension example, we could choose to sell the main extension to a local competitor for \$250 million.

These examples are formulated as binomial processes: two possible outcomes are considered at the end of the year. If an uncertain variable follows a binomial process, its value will either increase by an up movement to an up state, or decrease by a down movement to a down state. The magnitudes of the up and down movements, and their probabilities, depend upon the degree of uncertainty surrounding the movements of the variable. While a binomial formulation is convenient for expositional purposes, two possible outcomes at the end of a year is clearly an unrealistic depiction of most processes.

It turns out that this shortcoming can be easily addressed within the binomial framework,[6] as follows: Suppose that, rather than thinking of uncertainty on an annual basis, we take it in smaller pieces. Specifically, suppose we adjust our measure of annual uncertainty to an equivalent measure of quarterly uncertainty, and model proportionate up and down movements in the uncertain variable during each three-month period. That is, we allow for two possible outcomes at the end of the next three months. Then, from each of the outcomes three months from now, values of the

6. Cox, Ross and Rubenstein (1979).

FIGURE 5



uncertain variable will move up or down once again, in the same proportional increments, and so on. Formally, we are allowing for four binomial trials within the year.

There are many ways to incorporate estimates of uncertainty into event trees. One common formulation, which will be discussed in detail in the fifth section, produces the event tree shown in Figure 5. In this tree, a project's present value, PV, evolves to either PV^{+} or PV^{-} at the end of three months. From each of these nodes, project value can increase or decrease once again, with the same proportional up and down movements. Note that the branches recombine in that the PV^{+-} node can be reached from the starting node PV either by consecutive movements up then down, or by consecutive movements down then up. Therefore, allowing for four binomial trials within the year generates five possible outcomes at the end of the year, as shown in Figure 5. In general, allowing for T binomial trials produces T+1 future outcomes. Therefore, if we wish to pursue a binomial approach, we can make our formulation more realistic by allowing for more frequent binomial trials.

Note that, given fixed probabilities of up and down movements from each node, the outcomes at the extremes (nodes PV^{++++} and PV^{----}) are less likely than the moderate outcomes. For example, there is only one possible path to node PV^{++++}, which can be reached only by a series of four consecutive upward movements in the uncertain variable. The moderate outcomes, however, are much more likely to occur, as there are many more possible paths. For example, the central node PV^{++--} can be reached a total of six different ways.[7] The point is that, not only does increasing the number of binomial trials lead to a larger number of future outcomes, the distribution of the outcomes has the realistic property that moderate outcomes are more likely.

While allowing for five outcomes at the end of the year is more comfortable than allowing for two, we would be most comfortable in many situations by considering a continuous range of future outcomes. This can be accomplished by invoking the following principle: as the length of time between binomial trials approaches zero, the result is a continuous distribution of future possible outcomes of the uncertain variable. If the uncertain variable is the price of a security underlying an option contract, the binomial model converges to the Black-Scholes option pricing model, which is derived using complex tools of stochastic calculus. Interestingly, while the model is difficult to derive, it is easily implemented using a programmable financial calculator or one of several personal computer spreadsheet packages. In fact, if our option follows the assumptions of Black-Scholes, it can be valued in minutes.

The Black-Scholes model solves for option values as a function of five variables: exercise price, time to expiration, discount rate, the present value of the underlying asset, and volatility. It can be extended to the valuation of real options by recognizing the parallels between real and financial options, as follows:

7. In general, let T be the number of binomial trials and n be the number of upward movements to reach a node. The number of paths to the node is equal to [T!/((T-n)!n!)]. If we define p as the probability of an upward movement, the joint probability of reaching the node is found by multiplying the number of paths by $p^{n}(1 - p)^{T - n}$. See Copeland and Weston (1988), pp. 264-265.

Increasing the number of binomial trials not only leads to a larger number of future outcomes, but the distribution of the outcomes has the realistic property that moderate outcomes are more likely.

TABLE 1
BLACK-SCHOLES VALUATION OF PHARMACEUTICAL TIMING OPTION EXAMPLE, USING SIMPLIFYING ASSUMPTION FOR DISCOUNT RATE

Exercise price	$12 million
Time to expiration	365 days
Discount rate	20%
Volatility	110%
Value of underlying asset	$13.13 million
Black-Scholes valuation of plant investment as a call option	$6.6 million

1. The exercise price. For a capital investment project, this is the dollar value in the future (not discounted to the present) of the capital expenditures necessary to implement the flexible portion of the project. For example, this is the cost of the plant and equipment necessary to support full-scale production ($12 million) in the pharmaceutical illustration.
2. The time to expiration. The length of time before a decision must be made and capital committed. In all of our examples, this would be one year.
3. The discount rate, which is used to convert future amounts to present values.
4. The value of the underlying asset. For an option written on a share of stock, this is the current value of the share of stock; for a capital investment project, this is the present value of the cash inflows expected from the flexible portion of the project. For example, in the growth option (e-commerce) example, this would be the probability weighted average of $240 million and $135 million, discounted back to the present.
5. Volatility, as measured by the standard deviation (sigma) of the rate of growth in the value of the underlying asset. (Details on the estimation and interpretation of this measure of uncertainty will be presented in the fifth section.)

Let's apply the Black-Scholes model to the pharmaceutical timing option example. Here the exercise price is the $12 million investment to construct the plant one year from now. Time to expiration is 365 days (one year), and the discount rate (for simplicity) is 20%.[8] What about the volatility measure? While it appears that we haven't used a sigma in our calculations, a sigma of 1.1, or 110%, was used to determine the range of outcomes ($39 million to $4.3 million) and their probabilities.[9] Finally, the value of the underlying asset is our best estimate of the gross value of the opportunity today (before subtracting capital investments included in the exercise price). This estimate includes the present value of cash inflows that building the plant would generate, but does not take account of the fact that we only will invest in the plant in the up state. That is, the value of the underlying asset[10] is approximately

$$\begin{aligned} PV &= [(.33)(\$39.00) + (.67)(\$4.30)]/(1 + .2) \\ &= 13.13 \text{ million} \end{aligned} \qquad [9]$$

A summary of inputs, and the resulting Black-Scholes call option value, is shown in Table 1.

How does this compare to our binomial estimate of value? The Black-Scholes model tells us that the option to invest $12 million one year from now to construct a plant is worth $6.6 million. Our binomial evaluation (in equation [2]) told us that, after incorporating the $4 million investment for clinical trials, the project has a modified NPV of $3.4 million. This means that the option itself is worth $3.4 million plus $4 million, or $7.4 million. That is, the binomial valuation overstates the Black-Scholes valuation by $0.8 million, or approximately 11% of the binomial valuation. In fact, because the binomial method is an approximation to Black-Scholes, it will converge to the Black-Scholes value only as the number of binomial trials approaches infinity. As this example illustrates, the binomial value tends to approach the Black-Scholes value from above, slightly overstating the Black-Scholes value.

If the Black-Scholes model is so easy to implement and is characterized by a realistic distribution of future project values, why do we even discuss the binomial model? First, because the binomial model converges to Black-Scholes, it is useful for under-

8. Once again, this discount rate is not really correct; the appropriate discount rate will be discussed in Section IV.

9. The link between sigma and the range of outcomes will be outlined in Section V. For this example, the values of $39 and $4.3 were determined from an assumed underlying asset value today of $13 million and an annualized volatility of 110%. The careful and informed reader may calculate an implied volatility from the figures in Table 1 of approximately 108.9%. The difference between 108.9% and 110% is due to a series of rounding choices made throughout this example by the author.

10. Incidentally, it is correct to calculate the value of the underlying asset using the risk-adjusted discount rate.

standing the essence of option valuation while avoiding the complex mathematics used to derive Black-Scholes. Second, and more important, there are cases in which the Black-Scholes model does not apply, but where the binomial serves as a good approximation of the option's value. For example, the Black-Scholes model assumes that the expected value of the underlying asset grows over time at the risk-adjusted discount rate, and that the risk of the underlying asset is constant over time. Moreover, the Black-Scholes model works best if there is only one decision to be made on some future date, while the binomial model applies if there is a series of sequential decisions or multiple options.

Finally, we need to be very careful in defining Black-Scholes inputs for capital investment projects; it often is not as easy as it appears. The biggest difficulty is that many projects with option elements also include one or more assets-in-place. Consider the growth option example. The cash flows in the first year are not subject to any flexibility, and are properly valued with standard discounted cash flow techniques. Black-Scholes valuation requires the identification of assets-in-place where they are present, and the separation of assets-in-place from option elements for purposes of defining Black-Scholes inputs. This requires careful strategic framing of the project, and takes a little practice.

Table 2 presents a summary of the four examples, distinguishing assets-in-place from options and then mapping project attributes into the five Black-Scholes option valuation inputs. You will note that the discount rate for option valuation in Table 2 is the risk-free rate (the reason for which will be provided in the next section). Also, you will note that the underlying asset is always measured as the present value today of cash inflows from the flexible portion of the project, but ignoring the fact that these flows will be selectively captured. (This issue will be further explained in the fifth section.)

THE DISCOUNT RATE

Up to now, we've avoided the issue of the appropriate discount rate to use in option valuation, and we need to determine the rate appropriate for both the binomial and Black-Scholes approaches. We begin with the premise that the discount rate appropriate for discounting risky cash flows should reflect the risk of those cash flows. So, in determining the correct rate for discounting an option, the most obvious initial choice is the same risk-adjusted discount rate that we would use were we to value the project using the NPV rule (with no flexibility). But let us ask a fundamental question: Does a flexible claim on an asset (an option) have the same risk as the underlying asset itself? The answer is "no," for two reasons. On one hand, a flexible claim is less risky because capital investment in the future will be made only if favorable outcomes occur, and losses can be contained. On the other hand, an option is a levered claim on the underlying asset, where a small amount is invested now for potentially large (or zero) returns in the future. It is well understood that a levered claim is more risky than an unlevered claim (an outright investment) on the same underlying asset.[11]

So, since choosing an appropriate risk-adjusted discount rate is problematic, why not put the risk adjustment into the cash flows themselves? That is, let's compute the "certainty equivalent" of the risky cash flows. The certainty equivalent of a future risky payoff is the smaller, certain payoff that we would be willing to exchange for that uncertain future amount.[12] The benefit of this approach is that, if we can incorporate the risk adjustment into the cash flows, we can synthetically create riskless option payoffs and discount them at the risk-free rate.

To illustrate, let's return to the pharmaceutical development example. Recall that we expected a \$39 million payoff with a 33% probability, and a \$4.3 million payoff with a 67% probability. The expected value of payoffs one year from now is \$15.75 million:

$$\begin{aligned}\textbf{Risky expected value} &= (.33)(\$39.00) + (.67)(\$4.30)\\ &= \$15.75 \textbf{ million}\end{aligned} \qquad [10]$$

The present value of this risky expected future outcome can be measured by discounting at the risk-adjusted rate of 20%, as follows:

$$\begin{aligned}\textbf{Present value} &= \$15.75/(1 + 0.20)\\ &= \$13.13 \textbf{ million}\end{aligned} \qquad [11]$$

But there is another way to compute the present value of this risky expected future cash

11. See Hull (1995), p. 11; and, in this issue, Hodder and Mello (2001).

12. See Brealey and Myers (1996), p. 226.

As the length of time between binomial trials approaches zero, the binomial model converges to the Black-Scholes option pricing model. While the model is difficult to derive, it is easily implemented using a programmable financial calculator or one of several personal computer spreadsheet packages.

TABLE 2
SUMMARY OF FOUR OPTION TYPES WITH REGARD TO PRESENCE OF ASSETS-IN-PLACE AND BLACK-SCHOLES VALUATION INPUTS

	Timing Option (Pharmaceutical)	**Growth Option (E-Commerce)**	**Production Option (Copper Mine)**	**Abandonment Option (Main Extension)**
FIRST, DISTINGUISH ASSETS-IN-PLACE FROM OPTIONS...				
Asset-in-Place (Value using standard DCF approaches)	None	Present value of e-commerce cash inflows without adding capacity	Present value of $10 million outflow one year from now for fixed costs	Present value of future cash inflows to the main without selling to competitor
Option (Value using binomial or Black-Scholes approaches)	Call option: right to invest $12 million to construct plant	Call option: right to invest $200 million to employ excess capacity	Call option: right to invest variable costs of $35 million to refine copper ore	Put option: right to sell main extension to competitor for $250 million
...THEN, IDENTIFY BLACK-SCHOLES PARALLELS.				
Exercise price	$12 million	$200 million	$35 million	$250 million
Time to expiration	365 days	365 days	365 days	365 days
Discount rate (Options are valued using the risk-free rate for discounting [a])	5%	5%	5%	5%
Volatility	Annual standard deviation in rate of growth of the present value of cash inflows	Annual standard deviation in rate of growth of the present value of cash inflows	Annual standard deviation in rate of growth of the price of copper	Annual standard deviation in rate of growth of the present value of cash inflows (based on the price of natural gas)
Value of underlying asset (The underlying asset is valued using a risk-adjusted rate for discounting)	Present value of future expected cash inflows to drug, assuming it will be sold whether trials are successful or unsuccessful	Present value of future additional expected cash inflows to venture, assuming excess capacity is brought on line regardless of first year results	Present value of future expected cash inflows from copper sales, assuming copper will be mined regardless of copper price	Identical to the asset-in-place: present value of expected cash inflows to the main without selling to LDC

a. See the fourth section of this article.

flow. Let's change the actual estimates of probabilities (that is, 33% for the up state and 67% for the down state) to risk-neutral probabilities. Applying risk-neutral probabilities to the risky future outcomes results in a risk-free expected value. We are indifferent between this risk-free amount to be received with certainty and the risky $15.75, which is uncertain. Risk-neutral probabilities can be determined by noting that (1) an asset can have only one value at any point in time, and (2) that same value can be determined by discounting risky cash flows at the risk adjusted rate (as in Equation [11]), or riskless cash flows at the risk-free rate. Denoting unknown risk-neutral probabilities as p' and assuming a risk-free rate of 5%, we can assert the following equality:

$$\begin{aligned}\$13.13 &= [(.33)(\$39.00) + (.67)(\$4.30)]/(1 + .20) \\ &= [(p')(\$39.00) + (1 - p')(\$4.30)]/(1 + .05) \qquad [12]\end{aligned}$$

Because we have one equation and one unknown, this equality can be used to determine the risk-neutral probability of the up state as 27.3%. The expected value of future cash flows using risk-neutral probabilities, or the certainty equivalent of these cash flows, is:

TABLE 3
BLACK-SCHOLES VALUATION OF PHARMACEUTICAL TIMING OPTION EXAMPLE, CORRECTED TO USE RISK-FREE RATE

Exercise price	$12 million
Time to expiration	365 days
Discount rate (risk-free rate)	5%
Volatility	110%
Value of underlying asset	$13.13 million
Black-Scholes valuation of plant investment as a call option	$6.0 million

$$\text{Risk-free expected value} = (.273)(\$39.00) + (.727)(\$4.30) = \$13.77. \qquad [13]$$

Note that the certainty equivalent expected value, $13.77, is less than the risky expected value of $15.75. This will usually be the case; rational investors will be indifferent between a smaller future amount to be received with certainty and a larger, uncertain future amount. However, when the certainty equivalent $13.77 is discounted at the risk-free 5% rate, the present value of approximately $13.13 results.

Generalizing and re-arranging equation [12] to solve for p' yields the following expression for determining risk-neutral probabilities,

$$p' = [PV_0(1 + r) - PV_1^-]/(PV_1^+ - PV_1^-) \qquad [14]$$

where PV_0 is the present value today of the underlying asset, PV_1^+ is the present value in the up state one year from now, PV_1^- is the present value in the down state one year from now, and r is the annual risk-free rate of interest. Equation [14] can be used to determine directly the risk-neutral probability of an upward movement for the current example as follows:

$$p' = [13.13(1 + .05) - 4.30]/(39.00 - 4.30) = 27.3\% \qquad [15]$$

Think for a moment about what we've just done. Instead of putting the risk adjustment in the discount rate, we've put it into the probabilities that characterize our primary source of uncertainty—in this case the success of the clinical trials. Because we will only make our future capital investment in the up state, these probabilities also depict the likelihood of making the $12 million capital investment in the future. We therefore can use the risk-neutral probabilities and the risk-free rate to more correctly value the option inherent in the initial $4 million expenditure, as in the following refinement to equation [2]:

$$\text{Corrected NPV} = (-\$4) + ([(.273)(\$27.00) + (.727)(\$0.00)]/(1 + .05)) = \$3 \text{ million} \qquad [16]$$

While correcting the discount rate in this example does not reverse our recommendation, it does alter the NPV of the project by about 12% (from our original estimate of $3.4).

At this point, it should be clear that real options analysis is more than an application of decision trees.[13] It also requires an understanding of basic financial principles and a careful consideration of the discount rate. While we can finesse the discount rate issue by using, for example, actual probabilities and the risk-adjusted discount rate, any strictly correct binomial options analysis will use risk-neutral probabilities and the risk-free rate. Further, because the binomial and Black-Scholes models fundamentally are based on the same principles, any strictly correct Black-Scholes options analysis will also use the riskless rate as the discount rate.[14] At a risk-free rate of 5%, the Black-Scholes evaluation of the pharma example presented in Table 1 would be corrected to generate the result in Table 3.

Correcting the discount rate has reduced the Black-Scholes valuation of the option, from $6.6 million to $6.0 million, a decline of approximately 9% of the option value. $6.0 million is the correct Black-Scholes option value.

VOLATILITY: MEASUREMENT AND INCORPORATION

At this point, we have addressed four of the five factors necessary to conduct an option pricing analysis: time to expiration, underlying asset value, exercise price, and discount rate. It is interesting to note that these four factors can be extracted from the same information assembled to conduct a traditional

13. Trigeorgis and Mason (1987).
14. Actually, Black and Scholes derived their model by constructing *riskless hedges* of the uncertain future outcomes. Their model is identical, however, to a binomial approach using risk-neutral probabilities and the risk-free rate, when the number of binomial trials approaches infinity. See Cox, Ross and Rubenstein (1979).

The Black-Scholes model works best if there is only one decision to be made on some future date, while the binomial model applies if there is a series of sequential decisions or multiple options.

NPV analysis. However, there is one remaining implementation issue, and it involves gaining an understanding of a factor not explicitly required for an NPV analysis. This factor is uncertainty or volatility, and it must be estimated whether we plan to conduct a binomial or Black-Scholes analysis. For Black-Scholes, we need a measure of volatility as a model input. For a binomial formulation, we will need to use volatility to construct our event trees.

As mentioned in the third section, volatility is based upon uncertainty about the rate of growth in the value of the underlying asset. Specifically, for a real option, it is our best estimate of the standard deviation (sigma) of the rate of growth in the present value of the underlying asset. The first step in the estimation of volatility is a careful look at the project to determine its primary source of uncertainty. What is unknown today which, when it becomes known, will indicate the value-maximizing course of action? With luck, we can isolate the source of uncertainty in a single significant uncertain factor for which reasonable historical data exist, and measure it in a straightforward fashion. For example, in the abandonment (main extension) illustration, uncertainty would be modeled as the standard deviation in possible rates of growth of the price of natural gas between today and one year from now. It could be estimated based on a historical time series of prices of natural gas, using the assumption that the past is indicative of the future.

Typically, however, measurement of sigma is not this simple. For example, in the pharma timing option illustration, a reliable time series of historical data on the growth in value of a typical development effort likely will not exist. One solution would be to apply simulation analysis to the present value of the underlying asset to estimate the cumulative effect of many uncertain variables, and to draw inferences about sigma from the simulation. Another approach, used by Merck,[15] is to estimate volatility on the basis of the performance of a selected portfolio of biotechnology stocks, under the assumption that the volatility of this portfolio is reflective of the volatility of a typical development effort. While this approach has some intuitive appeal, it is important to note that the volatility of one firm's stock represents the volatility of a diversified portfolio of ongoing projects, and the volatility of a portfolio of stocks incorporates an additional diversification effect across firms. As such, volatility as measured by Merck will understate the volatility of a typical single project under consideration, and understate the estimate of option value accordingly. Perhaps such a measure of volatility is best incorporated as a conservative minimum volatility level. Finally, we could turn the question around as follows: How large would sigma need to be in order for the project to generate shareholder value? As noted earlier, greater volatility produces a greater option value, all else equal. It might be more comfortable to reason that volatility is greater than some threshold or breakeven level, than it is to measure it directly.

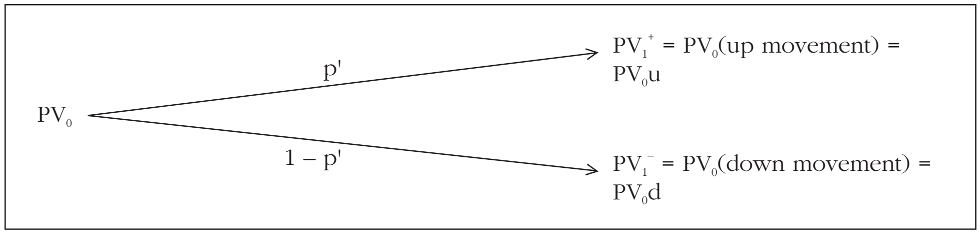
How does the Black-Scholes model incorporate the estimate of volatility? It begins with a measurement of the underlying asset, which is the present value today of expected cash inflows from the flexible portion of the project. The Black-Scholes model uses this value, together with the measure of volatility, to essentially map out a time path of future values of the underlying asset from today through the decision date, much like an expanded version of the event tree presented in Figure 5. The model then produces an option value that reflects rational exercise. For example, a call option's value solved by the Black-Scholes model reflects both the value that can be captured at expiration by exercising when the underlying asset value exceeds the strike price at expiration, and the likelihood of such occurrences.

While the Black-Scholes model is far easier to implement than a binomial approach, we know that it contains some restrictive assumptions that may not apply to our real option. If our option does not fit neatly into the Black-Scholes assumptions, we will need to apply a binomial approach, using our estimate of volatility to manually construct an event tree. As in the Black-Scholes model, we will begin our event tree construction with a measurement of the underlying asset value using standard DCF procedures. From this figure, the value of the underlying asset will evolve up and down.

Suppose that our primary source of uncertainty is future sales volume, and that sales volume realized after one year will dictate either a favorable or unfavorable payoff. Our up and down movements should reflect (1) our expectation of the average rate of growth in sales volume, (2) how uncertain we are

15. Nichols (1994).

FIGURE 6



about the growth rate of future sales volume, and (3) the logical constraint that sales volume measured one year from now is bounded from below at zero (that is, sales volume cannot be negative).

To begin, let's depict our problem in the following one-year, one trial context (see Figure 6). That is, PV_0 today (the present value of expected cash inflows) will grow to PV_0u with a p' probability, or decline to PV_0d with a (1-p') probability. A generally accepted way to model the up and down changes is shown in equation system [17],[16]

$$\begin{aligned} u &= e^{\sigma} \\ d &= 1/u \end{aligned} \qquad [17]$$

where e is the universal logarithmic constant equal to approximately 2.718, and σ is the expected annualized standard deviation in the rate of growth in PV. While equation system [17] may look unfamiliar, the up movement represents compounding PV at the rate of σ, while the down movement represents discounting PV at the rate σ. The use of the logarithmic constant e allows rate σ to be compounded continuously.[17] The level of σ determines the size of the up and down movements: the greater the uncertainty, the wider the range. Note that the multiplicative relationship between the up/down movements and the starting value provides a reasonable structure for our event tree, in that no matter how large is σ, the final distribution of outcomes cannot include negative values.

It often is necessary to stretch or shrink sigma from one measurement basis to another. The Black-Scholes model requires an estimate of annualized sigma, so we may need a way to stretch a sigma based on smaller time increments. On the other hand, we may wish to allow for a more realistic number of outcomes in a binomial analysis by converting an annualized sigma to a periodic equivalent figure.

For example, suppose we measure sigma from two years of monthly sales volume data from a similar product line. If we want to construct an event tree on an annual basis, or determine an annualized estimate of sigma for Black-Scholes, we need to stretch this monthly sigma to an annualized sigma. This can be accomplished through the use of a basic tenet of statistical theory: if a normally distributed random variable has standard deviation σ over time t, then its standard deviation over time T is $\sigma(T/t)^{.5}$. So, if we estimate a monthly standard deviation of 3%, the annual equivalent is

$$\text{Annualized } \sigma = 0.03(360/30)^{.5} = .03(12)^{.5} = 10.4\% \qquad [18]$$

Similarly, suppose we have an estimate of an annual standard deviation (say, 7%) and we want to construct an event tree with quarterly binomial trials. We can shrink the annual standard deviation to a quarterly measure as follows:

$$\text{Quarterly } \sigma = .07/(360/90)^{.5} = .07/4^{.5} = 3.5\% \qquad [19]$$

The event tree is constructed by allowing the value of the underlying asset to move up and down according to equation system [17], which would use an estimate of volatility consistent with the chosen time steps for the event tree. If we were valuing a call option assuming quarterly binomial trials and a one-year expiration date, for example, the event tree would look much like the one presented in Figure 5. The analyst would manually apply a decision rule to the five final nodes, assuming option exercise

16. Cox, Ross and Rubenstein (1979). This system for u and d is based on the assumption that that the rate of growth in PV between now and year-end is *normally* distributed, which is equivalent to assuming that the future distribution of PV is *lognormally* distributed. A lognormal distribution is skewed and bounded from below at zero. For more on distributional assumptions, see Hull (1995), Chapter 11.

17. We can roughly approximately equation system [17] using more familiar discrete compounding by allowing u to equal (1+σ). However, because the Black-Scholes model assumes continuous compounding, use of continuous compounding as shown in equation system [17] is recommended.

Perhaps the greatest barrier to the widespread practice of real options valuation is the knowledge barrier inherent in this newer, less understood approach.

where the value of the underlying asset exceeds the exercise price, and assuming the option expires worthless where the value of the underlying asset is less than the exercise price. The resulting values would be weighted by their probabilities[18] of occurrence, and discounted to present value at the risk-free rate to determine option value.

CONCLUDING REMARKS

The preceding discussion establishes that the presence of flexibility in capital investments fundamentally changes the methodology by which investment proposals should be analyzed. Borrowing from an established framework for security options, real options approaches allow us to quantify formally the value of flexibility.

This paper offers a practical approach to the understanding of real options, and synthesizes the structure by which such options can be identified and evaluated. Binomial examples are used to illustrate how options differ from assets-in-place, and how those differences affect their evaluation. We recognize that the simplicity of the binomial approach comes at a cost, in the form of an unrealistic distribution of two future outcomes. We present the Black-Scholes model as a special case of the binomial, in that the binomial model converges to Black-Scholes as the number of binomial trials approaches infinity. While the Black-Scholes model allows for a realistic continuous range of future outcomes and is quickly executed using a spreadsheet, it applies (without complex mathematical adjustments) only to real options characterized by one-time decisions. Also, the Black-Scholes model incorporates distributional assumptions that may not hold for the option being evaluated.

For example, production options entail successive periodic decisions to produce only when we can cover our variable costs of production. Extending the Black-Scholes model to more complex options is possible, but may not be the best use of the scarce time of many practitioners. These situations often are best handled by the more cumbersome, but more flexible, binomial approach. It is interesting to note that both option valuation approaches require the same information as a traditional NPV analysis, with one exception: options approaches require an explicit measure of risk.

The extension of option valuation approaches, which have developed in the context of securities markets, to the evaluation of real options is not without translation problems. The binomial and Black-Scholes approaches assume active trading in the underlying instrument; but real assets, of course, are not actively traded. Furthermore, in the Black-Scholes model, the exercise price and time to maturity are fixed by contract. For real options, both the level of the exercise price (future capital commitment) and the timing of this investment are uncertain.[19] Finally, the use of option techniques as a decision criterion is not time-tested. We will not know for some time whether firms practicing these valuation approaches make "better" investment decisions.

Perhaps the greatest barrier to the widespread practice of real options valuation is the knowledge barrier inherent in this newer, less understood approach. Sub-optimal investment decisions likely are resulting from managerial reluctance to incorporate real options analyses in investment proposals, and from managerial inability to fully understand the real options analyses prepared by others. It is important, despite the difficulties inherent in real option valuation, that practitioners develop an understanding of real options, including recognizing, creating, and valuing such options. Traditional NPV approaches simply do not appropriately value highly uncertain, actively managed projects, and many managers are in search of a better way. Learning option valuation approaches does require a non-trivial commitment, but these techniques are well within the capabilities of managers motivated to devote time to the issue. While this paper is not intended to transform the reader into a real options expert, it hopefully will give him or her the confidence and interest to learn more. At a minimum, an effort to understand real options facilitates a valuable change in mindset, an increased appreciation for the creation and preservation of flexibility in strategic investments.

18. It is important to remember that risk-neutral probability measurement must be consistent with the time steps chosen for event tree construction. For example, for quarterly binomial trials, the risk-free rate in equation [14] must be a quarterly rate, and the up and down state values must be quarterly estimates, determined from a quarterly sigma in equation system [17].

19. This concern is mitigated by our ability to determine a range of options values, using a range of possible exercise prices and expiration dates.

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Journal of Applied Corporate Finance (ISSN 1078-1196 [print], ISSN 1745-6622 [online]) is published quarterly on behalf of Morgan Stanley by Blackwell Publishing, with offices at 350 Main Street, Malden, MA 02148, USA, and PO Box 1354, 9600 Garsington Road, Oxford OX4 2XG, UK. Call US: (800) 835-6770, UK: +44 1865 778315; fax US: (781) 388-8232, UK: +44 1865 471775, or e-mail: subscrip@bos.blackwellpublishing.com.

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