

# Influence Diagrams for Real Options Valuation

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## Abstract

This paper proposes the use of Influence Diagrams (ID) as effective tools to model and place values on investment opportunities consisting of options on real assets (real options). We present an ID model to value a biotechnology firm, Agouron Pharmaceuticals, Inc., in terms of the sum of the values of its drug development projects. We compare the computed values of Agouron to actual market values at selected points in time during the development of Viracept, a drug used to treat HIV-positive patients. The ID model yields better estimates of the share prices than the values found using a binomial-lattice representation with the addition of a growth option. Our findings suggest that managerial flexibility in projects can be modeled and valued correctly using the Net Present Value methodology within an ID model.

**Keywords:** Decision analysis: Applications, Risk; Finance: Capital budgets, Investment.

# 1 Introduction

Real Options Analysis (ROA) has been proposed as an alternative methodology to evaluate capital investments such as R&D projects or new product decisions. The advantage of ROA is that unlike the Net Present Value (NPV) methodology used in capital budgeting, ROA treats a given investment opportunity as a single option or series of compound options, and thus captures asymmetric upside potentials embedded in the project. Well known texts like Trigeorgis (1996) and Dixit and Pindyck (1995) suggest that neither the discounted cash flow (DCF) approach nor the NPV framework can value correctly operational flexibility and other strategic aspects of investment projects because these rules make the false assumption that the investment is either irreversible or that it cannot be delayed. Similarly, Smith and McCardle (1999) criticize the cost-of-capital based discounting rule as the riskiness of the project in some cases may be significantly different than the firm's own risk structure.

With financial options, the initial investment in an options contract buys the potential opportunity to enjoy a positive cash flow in future propitious times, but does not carry the obligation to realize negative cash flow if adverse conditions prevail. This flexibility adds value to a financial option contract. With a real option—an option on a real asset—the initial investment in a project buys the potential opportunity to continue, expand, or abandon the project when it is advantageous to do so, but does not carry the obligation to realize some losses if the project faces adversity. As with financial options, the value of a real option is sometimes assessed by constructing an abstract hedge portfolio composed of the flexible project (with the option), the underlying asset, and cash. The idea is that as long as one can construct a portfolio that replicates the cash flows from the flexible project, a no-arbitrage argument can be used to value the project as a function of the value of the underlying asset and the funds borrowed against it.

The effectiveness of the ROA method in estimating the true value of an investment project depends on how well uncertainty is represented in the model. Indeed, ROA is be-

coming popular among corporations, investors, and governments because this methodology factors uncertainty and managerial flexibility into final valuation much better than do existing valuation methods.

Recently, Lander and Shenoy (1999) proposed the use of influence diagrams for representing uncertainty and flexibility in order to value real options. An influence diagram (ID) is a graphical modeling tool for representing the underlying structure of a problem and depicting the decision-maker's current knowledge about the situation. One major advantage of IDs is that the graphical representation makes it easy to depict uncertainty and managerial flexibility. Thus, investment projects that include sequential decisions, or projects that have an asymmetric structure due to managerial flexibility can be represented in a compact graphical manner, which can make it easier for decision-makers to understand complicated aspects of the problem. Further, because uncertainty in key underlying variables such as discount rates can be represented compactly within the ID framework, it is possible to use an NPV-based calculation for valuation instead of one that requires replicating portfolios and no-arbitrage arguments for illiquid assets, or certainty-equivalent probabilities that must be determined subjectively by the decision-maker.

The starting point of ROA is the suggestion that the traditional DCF and NPV methodologies are inadequate for evaluating projects containing embedded options, such as the option to expand, postpone, or abandon the project once it has begun. The traditional methods are based on the calculation of total value of projected cash flows discounted at a single discount rate that is selected on the basis of a subjective assessment of the riskiness of the project. A major problem with these methodologies is that they use a single discount rate for risky cash flows regardless of which conditioning scenario generates those cash flows. However, in most real-life investment projects, the flexibility embedded in future decisions changes the payoff structure and the risk characteristics of an actively managed asset, which in turn invalidates the use of a constant discount rate. Thus, the NPV and DCF

methods fail to value scenario-dependent cash flows correctly when projects are subject to active management. However, in a recent study, De Reyck, Degreave and Vandedborre (2002) suggest that flexibility in projects can be valued correctly with a decision tree as long as different discount rates that prevail at different chance nodes are determined properly. Brealey and Myers (2000) raise a similar point and suggest dividing projects into segments where the same discount rate can be used reasonably. This segmentation is handled easily with an ID.

In this paper, we show how to use IDs as effective tools to represent decision flexibility and uncertainty inherent in investment projects. We build on Kellogg and Charnes (2000) valuation model of Agouron Pharmaceuticals, Inc. and construct an ID model to represent and solve the same problem. We estimate share prices for Agouron at selected points in time during the development of Viracept, a drug used to treat HIV-positive patients. We then compare our computed values to actual market values as well as to the decision-tree and binomial-lattice estimates of Kellogg and Charnes (2000). We get better estimates of Agouron's stock price in 4 out of the 5 selected dates. With the exception of October 1994, the influence diagram improves the estimates by at least 10% in the worst case and by 32% in the best case. Our findings support the suggestion that the NPV-based methodology can be used effectively without relying on an analysis that requires the formulation of abstract hedge portfolios.

The outline of the paper is as follows. Section 2 provides brief information on Agouron Pharmaceuticals, Inc. and describes the risks inherent in new drug development. Section 3 outlines the assumptions made in the valuation of the project. Section 4 describes the decision tree, binomial lattice, and influence diagram valuations of Agouron. Section 5 presents the results obtained using the three methods and compares the values with actual share prices of Agouron. Finally, Section 6 provides concluding remarks and suggestions on future research.

## **2 Agouron Pharmaceuticals, Inc.**

Agouron was founded in 1984 and became a publicly traded company in 1987. Until 1997 the company had no operating income from products and most of its efforts focused on the discovery of new molecular entities (NMEs) and clinical trials thereof. Agouron also formed partnerships with larger pharmaceutical companies to collaborate on the discovery, development and commercialization of drugs based on biotechnology.

Such partnerships are common in the pharmaceutical industry. For the biotech companies, the partnerships provide credibility, capital, additional technical expertise and the means to market their products in many areas of the world where the larger company has established operations. For the larger pharmaceutical companies, the biotech companies provide additional sources of innovative ideas and become an extension of their existing R&D group. In a typical partnership the larger company acquires equity in the biotech company, and provides payments to the biotech company upon the initiation of a specified phase of development or governmental approval. The companies then share the resulting cash flows of the approved drug.

In July 1994, Agouron was conducting research on anti-cancer and anti-HIV compounds. It had two anti-cancer NMEs in Phase I clinical trials, and one anti-HIV NME in pre-clinical development. During the next four-and-one-half years, Agouron made several major announcements about the progress of its research and development. On January 26, 1999, Agouron announced that it was being acquired by Warner Lambert Co. for stock valued at \$US 2.1 billion.

### **2.1 New Drug Development**

Valuation of pharmaceutical companies that are in the development phase for new drugs is a challenging task. Investment projects involving new drugs are costly and highly risky. Of the virtually infinite number of molecular compounds that may have pharmacological effect, drug

companies must choose carefully the compounds in which to invest the millions of dollars in development costs required to launch a new product on the market. The development process is composed of several stages, during which the drug company gathers evidence to convince government regulators that it can consistently manufacture a safe and efficacious form of the compound for the medical condition it is intended to treat. At the end of each stage, the firm uses the technological and market information revealed up to that point to decide whether to abandon or continue development of the compound.

Drugs that reach the market in the United States typically pass through the following stages:

**Discovery.** In this stage, a significant amount of effort is expended by chemists and biologists to develop concepts for synthesizing NMEs. Many NMEs are abandoned at this stage.

**Pre-clinical.** The NME is screened for pharmacologic activity and toxicity *in vitro*, and then in animals. If the NME is a promising candidate for further development, the firm will file with the Food and Drug Administration (FDA) an Investigational New Drug (IND) application. An approved IND allows the firm to continue development by testing the drug on humans in clinical trials. Clinical trials are generally broken down into three phases.

**Phase I clinical trials.** Testing is conducted in a small number of (usually healthy) volunteers to obtain information on toxicity and safe dosing ranges in humans. Data are also collected on the drug's absorption and distribution within the body, the drug's metabolic effects, and the rate and manner in which the drug is eliminated from the body.

**Phase II clinical trials.** The drug is administered to a larger number of individuals selected from patients for whom the drug is intended to benefit. Successful Phase II trials

provide significant evidence of efficacy, and additional data on safety.

**Phase III clinical trials.** This final pre-marketing clinical development phase involves large-scale trials on patients to obtain additional evidence of efficacy. Larger sample sizes increase the likelihood that actual benefits will be found statistically significant, and that adverse reactions occurring infrequently in patient populations will be observed. Phase III trials are designed to approximate closely the manner in which the drug will be utilized after marketing approval.

**FDA filing and review.** After the clinical development phases have been completed and the firm believes it has sufficient evidence for approval, it will submit a New Drug Application (NDA) to the FDA for review. Marketing for approved uses may begin upon notification from the FDA.

**Post-approval.** While the firm receives revenues from the sales of its new drug, it conducts additional research to support marketing efforts and to develop extensions of the product. These extensions include alternate formulations and dosages for subsets of patients such as children.

### 3 Assumptions

In this paper, we compare the valuations obtained using an influence diagram with the valuations in Kellogg and Charnes (2000) obtained through the decision tree and binomial lattice methods. Therefore, we use many of the same assumptions they applied in their analysis. The assumptions about development costs, probabilities of success, and profitability of new drugs are based upon the work of Myers and Howe (1997), Office of Technology Assessment (1993), DiMasi, et al. (1991), and Grabowski and Vernon (1994). All costs and revenues are stated in 1994 constant dollars (\$US 000s).

We assumed that a drug reaching the market will fall into one of five quality categories: (1) dog, (2) below average, (3) average, (4) above average, or (5) breakthrough. A marketed drug has a 60% probability of being of average quality and a 10% probability of being in each of the other four categories. The revenues associated with each quality category are highly skewed, with the peak revenue for dog and below average drugs being no more than \$7.4 million per year and that of breakthrough drugs being over \$1.3 billion per year. The revenue for each category by year after launch is shown in Figure 1. Peak annual revenue by category is shown in Table 1.

Table 2 shows for each development stage the assumed pre-tax cost, duration in years, and probability of successful completion of that stage conditional on successful completion of the prior stages.

We assumed for R&D stages of duration greater than one year that total cost was allocated equally to each year. For some approved drugs, we assumed that post-approval clinical trials would be done. The purpose of these trials is to support the marketing effort for the drug. For example, the results of post-approval clinical trials are often cited in promotional literature that is presented to physicians by sales representatives. Without new information, it is often difficult for a sales representative to get the attention of a get busy physician. For drugs with low sales (dog or below average), we assumed that revenues will be insufficient to warrant post-approval clinical trials.

As are most products, drugs are subject to a product life cycle. The peak period of a drug's life cycle occurs just prior to patent expiration. After the patent expires, competitors may sell generic versions of the compound, and the competition causes revenues to drop. Myers and Howe (1997) do not include revenues beyond the peak year, as the post-patent-expiration revenues were not relevant to their analysis. We based our assumptions regarding post-patent years on the Office of Technology (1993) report. Table 3 provides details for other cash flow assumptions.

## 4 Valuation Methods

The efficient representation and solution of decision problems has always been a challenging task for academics and practitioners. Ideally, one is interested in models that are compact in representing different aspects of a decision problem as well as models that use efficient solution algorithms. In this section, we first present a brief discussion of the decision tree and binomial lattice valuations of Kellogg and Charnes (2000) and then provide the details of the influence diagram representation of the same project.

### 4.1 Decision Tree Method

Traditionally, decision trees (DT) have been used for the representation and solution of decision problems. This representation has its origins in von Neumann and Morgenstern's (1953) extensive form games. It is a flexible, graphical representation in which all possible scenarios are depicted as paths within a tree structure. For Agouron Pharmaceuticals, the decision tree valuation is done by calculating the expected net present value (ENPV) of the drug without taking into account growth options. The ENPV is calculated as:

$$\text{ENPV} = \sum_{i=1}^7 p_i \sum_{t=1}^T \frac{DCF_{it}}{(1+r_d)^t} + p_7 \sum_{j=1}^5 q_j \sum_{t=1}^T \frac{CCF_{jt}}{(1+r_c)^t}.$$

where  $i = 1, \dots, 7$  is an index of the seven stages from discovery through post approval described in Section 2.1,  $p_i$  is the conditional probability that stage  $i$  is the end stage for a drug that has reached stage  $i - 1$ ,  $T$  is the time at which all future cash flows become zero,  $DCF_{it}$  is the expected development stage cash flow at time  $t$  given that stage  $i$  is the end stage,  $r_d$  is the discount rate for development cash flows,  $j = 1, \dots, 5$  is an index of quality for the drug (defined in Section 3),  $q_j$  is the probability that the drug is of quality  $j$ ,  $CCF_{jt}$  is the expected commercialization cash flow at time  $t$  for a drug of quality  $j$ , and  $r_c$  is the discount rate for commercialization cash flows. This is represented graphically in Figure 2.

The use of different discount rates for development cash flows and commercialization cash flows follows Myers and Howe (1997), who based their selection of rates partly on Myers and

Shyam-Sunder (1996). We used real rates of 6% and 9% for development cash flows and commercialization cash flows, respectively. The inflation estimate was obtained from the average GDP deflator index over the prior five years from the date for which the valuation was made. For example, in calculating the ENPV of an NME in 1994 the inflation estimate was 3.58% resulting in nominal rates of  $r_d = 9.8\%$  and  $r_c = 12.9\%$ .

Table 4 shows the ENPV calculation of a discovery phase NME in spreadsheet form. This is done by determining the present value of all the possible end points and calculating the sum product of the present values and their respective probabilities. The values of each of the firms project ENPVs are adjusted according to the sharing agreements with partners, and are then summed and divided by the shares and warrants outstanding to obtain a per-share value for the firm. This spreadsheet is available at [www.siu.edu/~rdemire/ROA.htm](http://www.siu.edu/~rdemire/ROA.htm).

The decision tree framework has several advantages and disadvantages. For this particular problem, it is easy to construct and solve the tree because for any NME there will be no more than eleven potential end points. The fact that uncertainty is resolved at discrete points in time makes the decision tree framework quite practical. It is also easy to communicate using either tables or decision trees. This framework maps out all possible scenarios, and thus can model any possible path dependent cash flow pattern resulting from managerial flexibility. Finally, it incorporates the notion of an abandonment option as well as the potential of five scenarios of successful outcomes. However, the fact that all possible scenarios must be included in a DT leads to the combinatorial explosion of this representation, thus making DTs impractical for large scale projects. Consider a problem consisting of  $n$  decisions to be made and  $m$  uncertain outcomes to be observed at different stages of the problem. Even if we assume that each decision offers two possible choices and each uncertainty has two possible probabilistic outcomes, we come up with a decision tree consisting of  $2^{m+n}$  end points. Considering real life decision problems where a decision maker is faced with more than two choices at each decision (or more than two possible outcomes for each

uncertainty), DT representation may be unwieldy for large-scale problems. In addition, the DT framework, as solved in Kellogg and Charnes (2000) does not model volatility in the best way. Their use of discount rates applicable to commercial and non-commercial cash flows ignores the effect of managerial flexibility on the volatility of scenario dependent cash flows. This is, however, a problem common to all methods since the presence of an option makes it difficult to determine the appropriate discount rate applicable to different subtrees in a DT. However, as DeReyck et al (2002) suggest, this problem is resolved if the discount rates that prevail at different chance nodes are properly determined. In Section 4.3, we show that a simple modification within the influence diagram framework leads to better solutions than those obtained by the decision tree and binomial lattice methods.

## 4.2 Binomial Lattice Valuation

The solution algorithm for the binomial lattice method is based on the discrete-time binomial option pricing technique that was originally developed to value financial options (see Cox, Ross and Rubinstein, 1979). Starting in the 1980s, modifications of this method (and also its continuous-time version) have been used to value real options (Brennan and Schwartz, 1985, McDonald and Siegel, 1986, Pindyck, 1991, Dixit and Pindyck, 1994, Trigeorgis, 1996, Smith and McCardle, 1999). The underlying idea of the method is to assume a process for the stock price movements and use market data to represent time-risk preferences. The use of a traded security having similar risk and payoff characteristics to the project under analysis is the major advantage of this method over the traditional discounted cash flow approach. The key insight is that because the option values are independent of investors' risk preferences, the same valuations are obtained even when we assume that everyone is risk-neutral. This important assumption simplifies the calculations by eliminating the need to estimate the risk premium in the discount rate. See Amram and Kulatilaka (1998), Trigeorgis (1997), Kasanen and Trigeorgis (1994), and Mason and Merton (1985) for more on the use of risk-

neutral pricing.

One advantage of the binomial lattice method is the representation of the growth option inherent to the project. In the case of Viracept, the growth option is represented by a second binomial lattice for a research phase NME whose value at the time of launch of the first NME is added to the last branch of the first NME's binomial tree. This approach takes into account elements of Copeland's (1998) discussion of compound rainbow options, and Amram and Kulatilaka's (1998) description of periodic reevaluations of decisions using a binomial approach.

The key inputs to the binomial lattice are: (i) current value of asset,  $A$ ; (ii) standard deviation of the asset,  $\sigma$ ; (iii) risk free rate,  $r$ ; (iv) amount and timing of the exercise prices; and (v) probability of proceeding to the next phase of development. The value of Viracept at 6/30/94 is used to illustrate the calculation. The current value of the asset,  $A$ , is found by discounting the value of the expected commercialization cash flows to time zero:

$$A = \sum_{j=1}^5 q_j \sum_{t=1}^T \frac{CCF_{jt}}{(1+r_c)^t} = 123,921.$$

An  $n$ -period binomial lattice of asset values is constructed period by period. In the first period there are two possible outcomes,  $Au$  and  $Ad$ . In the second period there are three possible outcomes,  $Au^2$ ,  $Adu$ , and  $Ad^2$ . The process of considering all possible combinations of up and down movements of the asset value for each period is continued until the  $n^{\text{th}}$  period, which has end branch values  $E_k$ ,  $k = 1, \dots, n + 1$ . Figure 3 illustrates a binomial lattice that represents four periods.

Following Amram and Kulatilaka (1998), we set  $u = e^\sigma$  and  $d = e^{-\sigma}$ . Because we want the value of the NME to be able to grow from  $A$  to a maximum value of  $h$  after  $l$  years, we require  $h = Au^l = Ae^{\sigma l}$ . The value  $h$  represents the present value of a breakthrough drug at the time of launch. For  $l = 12$  and  $h = 2,875,675$ , we get  $\sigma = (1/l) \ln(h/A) = 26\%$ . Thus,  $u = 1.300$  and  $d = 0.769$  for a 12-year binomial lattice with one price change per year.

The next step is to add in the value of the growth option. Engaging in the development of an initial NME is analogous to purchasing a call option on the value of a subsequent NME. By engaging in development of the initial NME, the firm earns the right but not the obligation to develop the subsequent NME. The assumptions for the growth option are identical to the first option. The value of the growth option at the time of the launch of the first NME is added to each of the  $E_k$  values of the first NME.

Once the binomial tree of asset values is completed, the next step is to calculate the possible payoffs and roll back the values using risk neutral probabilities. The possible payoffs are calculated as  $P_k = \max[E_k(\theta_t) - DCF_t, 0]$ , where the value  $\theta_t$  is the probability of continuation to the next year in year  $t$  (in this case, 75%), and  $DCF_t$  is the R&D payment that occurs in year  $t$  (\$1,619). Because the value at launch of an NME is large (even if it is a dog) relative to the last year's R&D payment (exercise price) the possible payoff is very rarely (if ever) going to be zero.

The  $P_k$  values are then rolled back by multiplying the adjacent values, such as  $P_1$  and  $P_2$  (denoted  $V_{t+1,k}$  and  $V_{t+1,k+1}$ ) by the respective risk neutral probabilities  $p$  and  $(1 - p)$ , the probability of continuation to the next year, and a discount factor to obtain  $V_{t,k}$ . The risk neutral probabilities are computed as:

$$p = \frac{e^{r\Delta t} - d}{u - d},$$

where the risk free rate,  $r$ , is the 10-year United States Treasury-bill rate, which was 7.09% in 1994. This results in  $p = 0.573$ . Table 5 shows all the possible payoff values.

As the option values are rolled back, they are also adjusted for the probability of success at that phase of development and for the cost of development in that year. Thus the roll-back option values are:

$$V_{t,k} = \max[(pV_{t+1,k} + (1 - p)V_{t+1,k+1})e^{-r\sqrt{\Delta t}}\theta_t - DCF_t, 0].$$

For a development stage having a duration of more than one year,  $\theta_t$  is the probability

of success for that stage in the final year of that stage and 1 for all other years. The amount  $DCF_t$  can be regarded as an annual exercise price. For example,  $V_{12,1}$  is calculated as follows:

$$(2,156,669(.573) + 1,276,979(1 - .573)).9316(1) - 1,564 = 1,657,654.$$

This process is then continued until  $V_{1,1}$  is reached, which is the value of the firm.

### 4.3 Influence Diagram Representation

An influence diagram is a powerful decision analysis tool for representing and solving decision problems. It combines a graphical model that represents the underlying structure of the problem with a numerical database that represents the uncertainty and value associated with the variables in the model. An ID representation of a decision problem was initially proposed as a more compact prelude to constructing a DT representation (Miller et. al, 1976, Howard and Matheson, 1981). One major advantage of IDs is that the graphical representation grows linearly with the number of variables in the problem whereas decision trees and binomial trees grow exponentially. So, decision problems that include sequential phases (as in real options) can be represented in a more compact way thus making it easier for the decision-maker to see different aspects of the problem. From the practitioner's perspective, an ID representation is both intuitive and compact, so it is a powerful tool for communication, elicitation, and detailed representation of a decision maker's knowledge (Shenoy, 1994).

In addition to the representational compactness, IDs also have advantages for the solution of the problem. The key is to decompose uncertainty and utility into separate functional forms and then solve the problem locally (Olmsted, 1983 and Shachter, 1986). This approach leads to a great deal of efficiency at the solution phase, especially for large scale problems. Furthermore, the automation of ID representation with easy-to-use software has made IDs very popular for representing and solving decision problems.

Assuming that utility and uncertainty are specified correctly, an influence diagram is equivalent to a decision tree model, i.e., both solution techniques yield the same optimal

strategy. Further, Smith and Nau (1995) argue that, under certain conditions, a decision tree model gives the same results as an option-based model. These arguments support the idea that IDs can be a useful tool to represent and solve real options problems. As we show later, representation of different underlying sources of uncertainty through IDs improves the predictive capability of the model and leads to better estimates of Agouron’s share value than the decision tree and binomial lattice valuations.

In the case of Agouron, the firm’s decision problem includes seven phases. At each phase, the firm first observes the results of tests for that phase. The firm then makes a decision whether to continue or abandon the project. So, having observed test results, the firm has the option to abandon the project at the end of each phase. If the firm decides to abandon the project at a given phase, then the outcome for that phase is called a failure. Therefore, the outcome of a given phase is represented by two states —*success* or *failure*. However, this problem has an asymmetric structure because not all the possible outcomes are allowed at each phase of the project. For example, if the project is abandoned at phase  $t - 1$ , i.e. the outcome for that phase is failure, this implies that the project at phase  $t$  has already been abandoned. Thus, we will collapse all the future outcomes of the remaining phases into one outcome called *no result*. Such an asymmetric structure is common to many real options problems. However, although the asymmetric structure can be used to simplify the DT representation, inclusion of additional uncertainties (discount rates, inflation, volatility, etc.) in the model may still make the DT representation impractical for large-scale problems.

The influence diagram for Agouron is given in Figure 4. In an influence diagram, decisions, chance, and value variables are represented as separate nodes.

**Decision nodes:** The decisions available to the decision-maker are represented using rectangular nodes in the ID. The investment project consists of seven phases Discovery, Pre-clinical, Phase 1, Phase 2, Phase 3, FDA Filing, and Post-approval. At each phase, the firm has two alternatives: continue or abandon the project. However, the structure of Agouron’s decision

problem does not require the use of decision nodes because the decision is implied by the outcome of each phase. More specifically, at each decision point, having observed the results of each development stage of the project, the decision maker has the option of continuing or abandoning the project. By definition, once it is decided that the project should be abandoned, then the outcome is called a failure; otherwise it is called a success. Therefore, the ID model represents these implied decisions for the abandonment options using chance nodes only. We represent this asymmetric structure of decisions through the probability distribution of chance variables as explained next.

**Chance nodes:** Uncertainty is represented through the use of chance variables depicted as single-border oval nodes in the diagram. The ID for Agouron includes ten chance variables. The nodes Real NCDR,  $I$ , and Real CDR represent the real non-commercial, inflation, and the real commercial discount rates respectively. Each of these rates is a random variable used in the present value calculations of project cash flows for different stages. The probability distribution for inflation is obtained by using annual inflation values for the years 1983 to 1997. We approximated the continuous distribution for this variable using the bracket-median method of Clemen (1991). There are several other methods available to discretize continuous distributions; however, we chose one of the simplest methods because the selection of a discretization method is not a major focus in this paper. The reader is referred to Smith (1993) for a comparison of different discretization methods.

For Real NCDR and Real CDR, we used 6% and 9% respectively to be comparable with the DT model used in Kellogg and Charnes (2000). However, assigning a probability distribution to real rates of return is easy with an ID and allows us to extend the DT model. The remaining seven chance variables are D, PC, P1, P2, P3, FDA, and PostAp. These variables represent the uncertain outcome of the seven phases of the project as success ( $s$ ), failure ( $f$ ) or no result ( $nr$ ) if the previous phase has failed. For example, the node PC in the diagram represents the uncertain outcome of the Pre-clinical phase and has state space  $(s, f, nr)$ . The variables

represented by the ID nodes are summarized in Table 6.

One major advantage of the influence diagram is the compact representation of uncertainty in the model. An arrow between two chance nodes indicates a conditional probability distribution linking the two chance variables. For example, the arrow from node  $D$  to node  $PC$  indicates that the outcome of the Pre-clinical phase is conditioned on the outcome of the Discovery phase. Similarly, the arrow from  $P1$  to  $P2$  indicates the conditional distribution of Phase 2 results given the outcome of Phase 1. One special structure we implement in the model is to assign 100% probability to outcome *no result* (nr) in project stage  $t$  if the outcome of stage  $t - 1$  is either *failure* or *no result*. So for example, the conditional probability distribution for Phase 2 given Phase 1 is

$$P(P2|P1) = \begin{cases} 0.75(s), 0.25(f), 0(nr) & \text{if } P1 = s \\ 0(s), 0(f), 1(nr) & \text{if } P1 = f \\ 0(s), 0(f), 1(nr) & \text{if } P1 = nr \end{cases}$$

Using conditional probability distributions in the influence diagram allows us to factorize the global uncertainty into local factors. In the context of Agouron, this means that the outcome of stage  $t$  is independent of the outcome of stage  $t - 2$  given the outcome of stage  $t - 1$ . For example, knowledge of the outcome of Phase 3 is all we need for inference on the outcome of FDA filing phase. Mathematically this means  $P(FDA|D, PC, P1, P2, P3) = P(FDA|P3)$ . The structuring of nodes  $D$ ,  $PC$ ,  $P1$ ,  $P2$ ,  $P3$ ,  $FDA$ , and  $PostAp$  in the ID represents a factorization of uncertainty into the following form:

$$\begin{aligned} P(D, PC, P1, P2, P3, FDA) &= P(D) \cdot P(PC|D) \cdot P(P1|PC) \cdot P(P2|P1) \\ &\quad \cdot P(P3|P2) \cdot P(FDA|P3) \cdot P(PostAp|FDA) \end{aligned}$$

The uncertainty representation for project outcomes at each phase represents the decision maker's option to abandon the project after observing the results of a given phase. Once it is decided that the project should be abandoned at a particular phase of the project, then the outcome is deemed a failure.

**Deterministic nodes:** In addition to chance variables, we use double ovals to represent the deterministic variables that have only one possible outcome given the state of its predecessors. A deterministic variable is a special case of a chance variable that takes on a single deterministic value as a function of its predecessors. For each deterministic variable, we specify a mathematical function that yields its value. We used two groups of deterministic nodes: The first group consists of variables  $NCDR$  and  $CDR$ , i.e. the nominal non-commercial and commercial discount rates. The variables are deterministic functions of their probabilistic predecessors as

$$\begin{aligned} NCDR &= \left[ (1 + I) \cdot (1 + RealNCDR) \right] - 1 \\ CDR &= \left[ (1 + I) \cdot (1 + RealCDR) \right] - 1 \end{aligned}$$

The second group of deterministic variables consists of cash flow variables for each of the seven phases of the project:  $CF(D)$ ,  $CF(PC)$ ,  $CF(P1)$ ,  $CF(P2)$ ,  $CF(P3)$ ,  $CF(FDA)$ ,  $CF(PostApp)$ . We choose to define cash flow variables locally for each phase as this simplifies the ID both in terms of representation and also solution. The value of each cash flow variable is determined by the outcome of the particular phase, the projected cost/revenue figures, and the values of discount rate and inflation. We used the non-commercial discount rate for the phases, discovery through FDA filing and the commercial discount rate for the commercial phase,  $PostAp$ . In order to make the point clear, consider the first phase which is the discovery. Its duration is estimated to be one year and the cost of this phase is estimated as \$2,200 (all cost and revenue figures in \$000s). If the decision maker decides to abandon the project at this particular phase, then the outcome is called a failure and we are left with the costs already incurred in this phase. However, if we decide to continue the project, the outcome is called a success and the cash flow contribution is zero for that particular phase. Therefore, the cash flow node for the discovery phase,  $CF(D)$ , contains the formula

$$CF(D) = \begin{cases} 0 & \text{if } D = s \\ \frac{-2200}{(1+NCDR)} & \text{if } D = f \end{cases}$$

So, given the state of noncommercial discount rate and the outcome of the *Discovery* phase,  $CF(D)$  has no uncertainty. However, as we continue the project, we account for the effects of inflation, so the remaining cash flow nodes contain the inflation variable as an additional input. Let us now consider the next phase, the pre-clinical phase. Pre-clinical studies take three years and the estimated total cost for this phase is \$13,800. We assumed that this cost will be equally distributed through years during this phase, so we divide this total cost estimate into three. However, since these costs are defined in today's terms, we increase the costs at the rate of inflation. Finally, we calculate the net present value for the cash flows at this phase by discounting at the non-commercial discount rate. If we decide to abandon the project after the Preclinical phase, the total cash flow incurred is what has been spent until the previous phase,  $CF(D)$ , plus what is spent in the current phase, i.e.

$$CF(PC) = \begin{cases} 0 & \text{if } D = s \\ \frac{-2200}{(1+NCDR)} - \frac{13800}{3} \left[ \frac{(1+I)}{(1+NCDR)^2} + \dots + \frac{(1+I)^3}{(1+NCDR)^4} \right] & \text{if } P1 = f \\ 0 & \text{if } PC = nr \end{cases}$$

The cash flow variables for all the non-commercial phases *Discovery* through *FDA Filing*, are formulated similarly. The final phase is the Post-Approval phase, where the revenue estimates come into play. The cash flow variable for this phase,  $CF(PostAp)$ , is formulated in a similar manner, however this time the commercial discount rate is used in the calculations. We used the annual revenue estimates for the next 23 years after the launch of the product (see Figure 1), which are taken from Kellogg and Charnes (2000). We have five series of revenue estimates each for a particular outcome of the final stage, 'dog' through 'breakthrough'. Revenue estimates are defined in future value terms, so inflation does not appear in the formulas; however, we discount these numbers at the commercial discount rate. So, the cash flow for this phase includes what has been incurred as accumulated costs so far plus the net present value of the revenues for the next 23 years. Clearly, these revenue streams will be a function of the outcome of this phase. Although the expression is long, the following should make the point clearer.

$$CF(PostAp) = \begin{cases} -\text{Cost}(FDA) + \frac{-42,843}{(1+CDR)^{14}} + \dots + \frac{270,727}{(1+CDR)^{36}} & \text{if } PostAp = bt \\ -\text{Cost}(FDA) + \frac{-42,843}{(1+CDR)^{14}} + \dots + \frac{135,363}{(1+CDR)^{36}} & \text{if } PostAp = aa \\ -\text{Cost}(FDA) + \frac{-6,407}{(1+CDR)^{14}} + \dots + \frac{13,537}{(1+CDR)^{36}} & \text{if } PostAp = a \\ -\text{Cost}(FDA) + \frac{-84,674}{(1+CDR)^{14}} + \dots + \frac{1,521}{(1+CDR)^{36}} & \text{if } PostAp = ba \\ -\text{Cost}(FDA) + \frac{-93,141}{(1+CDR)^{14}} + \dots + \frac{1,353}{(1+CDR)^{36}} & \text{if } PostAp = d \\ 0 & \text{if } PostAp = nr \end{cases}$$

where  $Cost(FDA)$  is the sum of the costs of all prior stages including FDA filing, i.e. *Discovery through FDAfiling*.

**Value node:** The net present value of the entire project is calculated in this node. This value is simply the sum of contributions of each stage of the project, i.e.

$$NPV(Project) = \sum_{s=D}^{PostAp} CF(s)$$

## 5 Results

In this section we present our estimates of Agouron's share values for five selected dates and compare the results with actual stock prices as well as the estimates from Kellogg and Charnes (2000). The influence diagram gives us an estimate for the net present value of the Viracept project. We compute the value of Agouron Pharmaceuticals, Inc., as the sum of the values of its current projects, the largest of which by far was Viracept. Finally, we calculate the per share value of Agouron after dividing this sum by the number of fully diluted shares, i.e. shares outstanding plus warrants issued. Table 7 shows the values of Agouron Pharmaceuticals, Inc. obtained using the influence diagram, decision tree and binomial lattice methods. The actual stock prices are also shown for comparison.

The significance of the selected dates is

1. June 1994—fiscal year end. Viracept was undergoing preclinical trials;
2. October 20, 1994—announcement that Viracept would begin Phase I trials;

3. June 1995—fiscal year end;
4. June 1996—fiscal year end; and
5. December 23, 1996—announcement that Agouron was filing a New Drug Application (NDA) for Viracept.

One advantage of the ID framework is that valuation of the project for selected dates is done simply by entering evidence on selected sources of uncertainty in the problem. For example, consider the October 20, 1994 valuation. We know that the Discovery phase had passed successfully so this is entered as evidence to the node representing the outcome for this phase, i.e. node D. Our results indicate that the influence diagram can be a powerful alternative to the decision tree and binomial lattice models. We get better estimates on 4 out of 5 selected dates. With the exception of October 1994, the influence diagram improves estimates by at least 10% in the worst case (December 1996) and by 32% in the best case (June 1995). This is not a surprising result as further inclusion of fundamental sources of uncertainty should lead to better estimates. One should note that this can be done within the decision tree or binomial lattice framework; however, this would very much enlarge the representation and complicate the solution of these models. Our main point is that influence diagrams are extremely useful because they represent compactly the uncertainty underlying real options and thus enable us to represent and solve a larger class of models than we can with the DT and binomial lattice techniques. Furthermore, scenario-dependent discount rates, i.e. discount rates applicable to path-dependent cash flows resulting from managerial flexibility, can be modeled effectively using an ID, which in turn makes it possible to use an NPV-based methodology to value real options.

Table 7 indicates that all methods valued Agouron relatively well when the project was in Phase I or earlier, but the calculated values deviated further from the actual stock price as Viracept worked its way through the development process. Thus it appears that investors

were making different assumptions regarding the later development stages of this NME than they would have made for the typical NME specified in the model. If so, and if our model is adjusted for these assumptions, we expect that the valuation given by the model would be much closer to the actual stock price.

There are several reasons to believe that investors were making different assumptions. First, there was tremendous political pressure for the FDA to approve drugs for HIV-positive patients. Therefore, investors might have assumed that it would take less than eight years from beginning of Phase II until launch. In fact, it took slightly less than two years. Another important assumption is the probability distribution of the revenue stream. An assumption of our model is an 80% probability that revenue will be under \$100 million per year at peak. In fact, sales of Viracept were over \$400 million during fiscal year 1998 (its first full year of sales) and were \$548M in 1999 per NDCHealth. Again, it is likely that the market was assuming a different probability distribution for revenue. Finally, it is likely that the market assumed a probability of approval for Viracept greater than that for a typical NME.

## 6 Conclusion

This paper suggests using influence diagrams as an effective tool to value real options. We use an influence diagram to compute the value of a biotechnology firm, Agouron Pharmaceuticals, Inc., as the sum of the values of its current projects. We estimate share prices for Agouron at selected points in time during the development of Viracept, a drug used to treat HIV-positive patients. We then compare our computed values to actual market values as well as to the decision tree and binomial lattice estimates of Kellogg and Charnes (2000). The influence diagram yields better estimates of Agouron's stock price on 4 out of the 5 selected dates. With the exception of October 1994, the influence diagram improves the estimates by at least 10% in the worst case and by 32% in the best case.

A major advantage of the influence diagram framework is that it allows for compact

representation of different fundamental sources of uncertainty as well as scenario-dependent cash flows resulting from managerial flexibility. In the case of Agouron, a simple modification to discount rates improves the predictive capability of the model and leads to better estimates of the company's share value as compared to the decision tree and binomial lattice valuations. Considering the representation side of the problem, an influence diagram is more descriptive than a binomial lattice and it can represent real options problems that involve multiple uncertainties and sequential decisions much more compactly than a decision tree. Further, the process of building the ID requires communication among analysts and decision makers that leads to a better model. Considering the solution aspect, influence diagrams make use of conditional independence arguments that allow factorization of global uncertainty into smaller, local domains. Finally, our results add support to the suggestion that managerial flexibility in projects can be valued using the net present value framework, if applied correctly. The fact that scenario-dependent discount rates, i.e. discount rates applicable to path-dependent cash flows resulting from managerial flexibility, can be modeled in an effective manner using an ID, makes it possible to use an NPV-based methodology to value real options. Influence diagrams should be considered by corporate managers as a powerful alternative for the representation and solution of real options.

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Figure 1: Revenue streams (\$US millions, on logarithmic scale) for new drugs by quality category. Sources: Years 1–13 from Myers and Howe (1997), Years 14–24 from OTA.

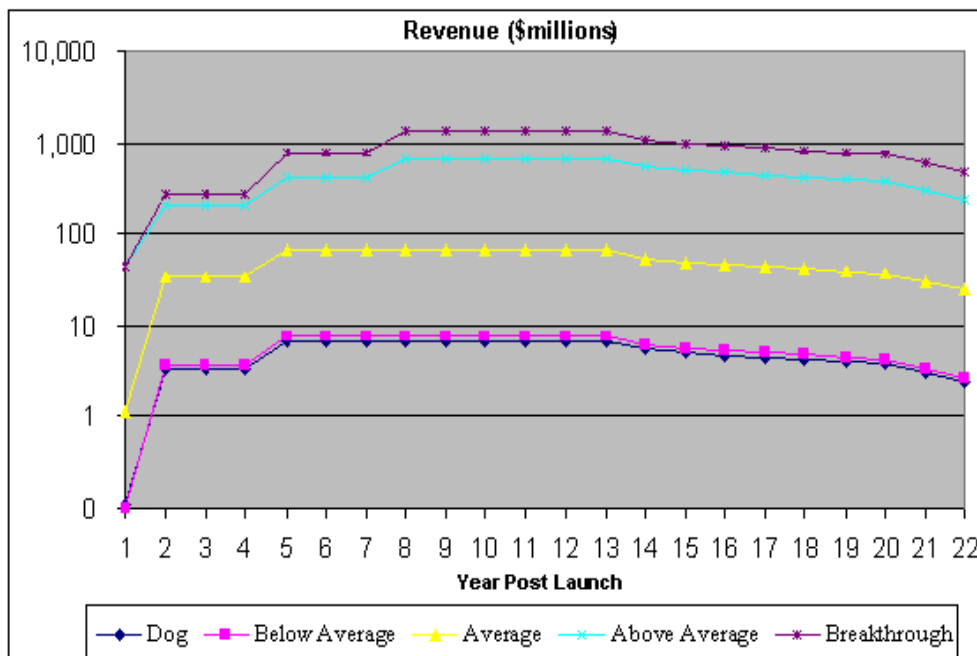


Figure 2: Decision Tree for Pharmaceutical Development

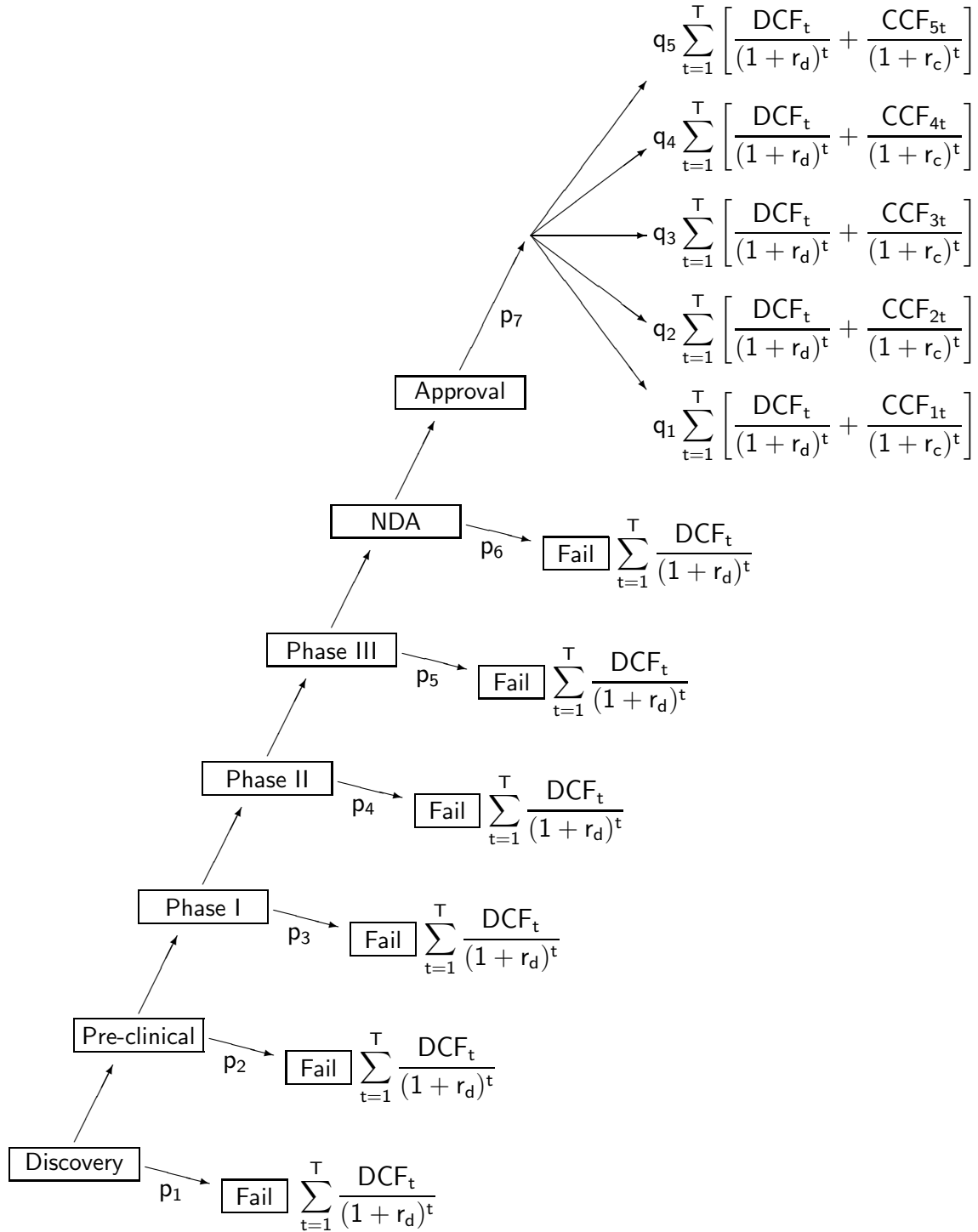


Figure 3: Four-Period Binomial Lattice

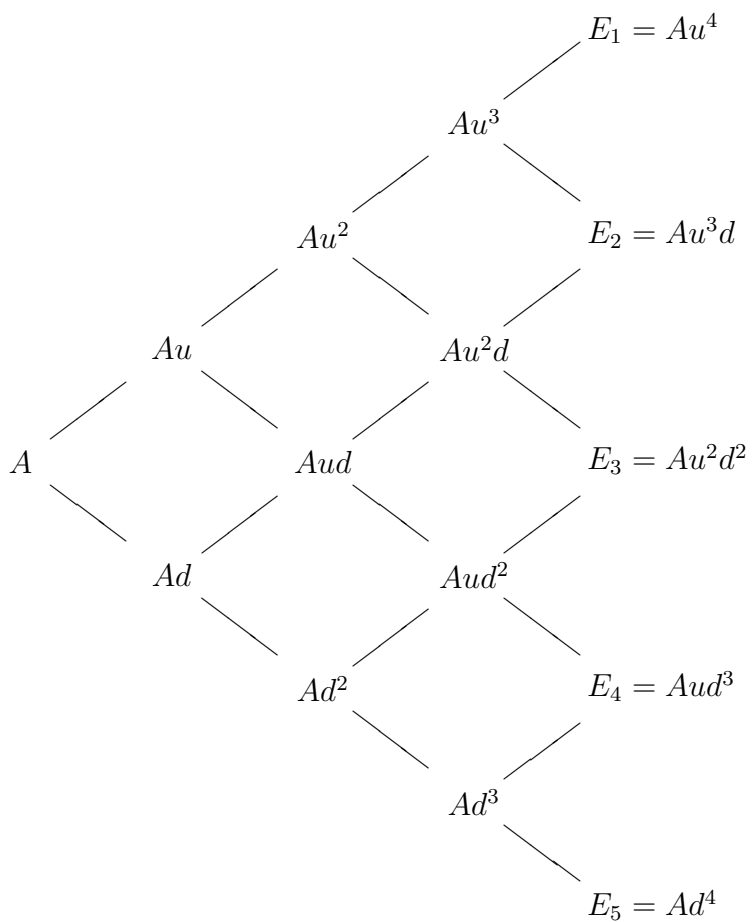


Figure 4: The ID representation of Agouron's decision problem for Viracept.

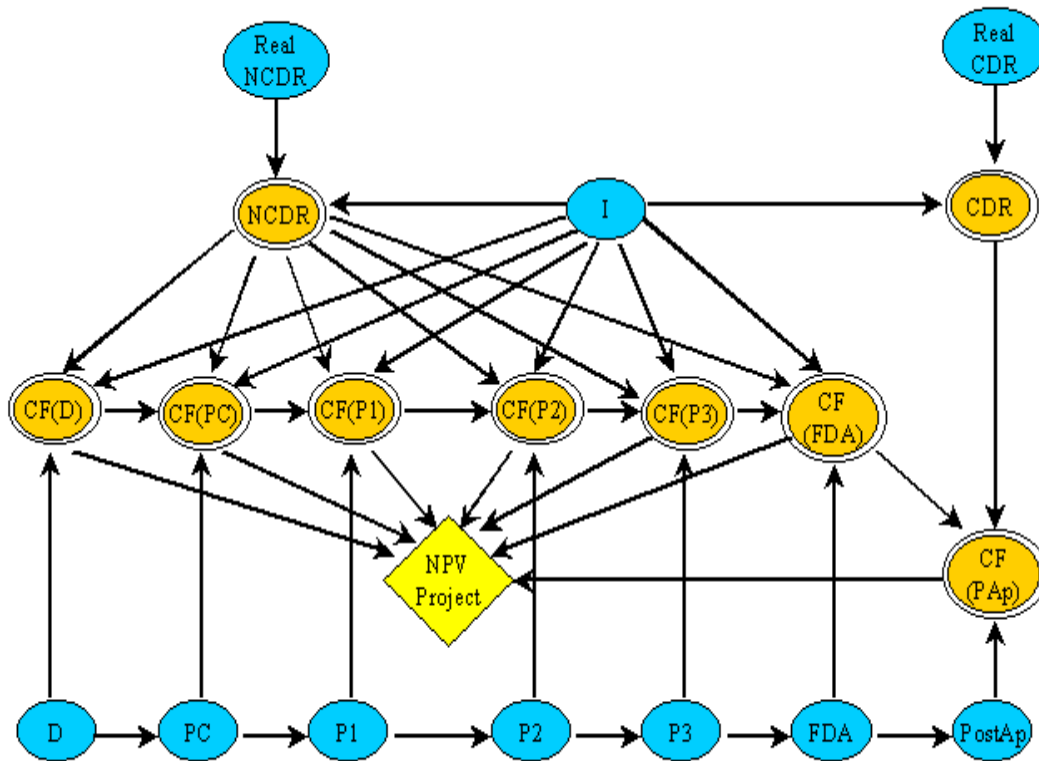


Table 1: Peak annual revenue (\$US 000's) by quality category. (Source: Myers and Howe, 1997)

<b>Quality</b>	<b>Peak Revenue</b>
Breakthrough	1,323,920
Above Average	661,960
Average	66,200
Below Average	7,440
Dog	6,620

Table 2: Pre-tax costs of development, durations and conditional probabilities of success for drug research and development stages. (Source: Myers and Howe, 1997)

<b>R&amp;D Stage</b>	<b>Total Cost (\$000s)</b>	<b>Years in Stage</b>	<b>Conditional Pr(success)</b>
Discovery	2,200	1	.60
Pre Clinical	13,800	3	.90
Phase I	2,800	1	.75
Phase II	6,400	2	.50
Phase III	18,100	3	.85
FDA Filing	3,300	3	.75
Post-Approval	31,200	9	1.00

Table 3: Other assumptions.

<b>Item</b>	<b>Assumption</b>	<b>Source</b>
Cost of Revenue	25.5% of revenue	OTA
Marketing Expense	100% of revenue in the first year after launch 50% of revenue in year 2 after launch 25% of revenue in years 3–4 after launch 20% of revenue in years 5–13 after launch	Myers
G&A Expense	11.1% of revenue	OTA
Tax Rate	35% of profit	Myers
Working Capital	17% of Revenue	OTA

Table 4: ENPV Calculation of a discovery phase NME in 1994 (\$US 000s)

End Phase	$i$	$j$	(1) $p_i$	(2) $q_j$	(3) $\sum_{t=1}^T \frac{DCF_t}{(1+r_d)^t}$	(4) $\sum_{t=1}^T \frac{CCF_{jt}}{(1+r_c)^t}$	((4) - (3)) $\times (1) \times (2)$
Discovery	1		.400		2,004		-802
Pre-clinical	2		.060		13,203		-792
Phase I	3		.135		15,223		-2,055
Phase II	4		.203		19,455		-3,949
Phase III	5		.030		29,810		-894
NDA submission	6		.043		31,395		-1,350
Approval	7		.129				
Dog		1		.10	31,395	3,762	-356
Below average		2		.10	31,395	4,230	-350
Average		3		.60	31,395	33,011	125
Above average		4		.10	31,395	315,819	3,669
Breakthrough		5		.10	31,395	615,013	7,529
ENPV = 775							

Table 5: Calculation of the possible Payoff values (\$US 000s) for  $DCF_t = 1,619$ ,  $\theta_t = 0.75$ , and value of growth option = \$2,085.

$k$	$E_k$	$P_k$
1	2,877,759	2,156,699
2	1,704,795	1,276,976
3	1,010,273	756,085
4	599,041	447,661
5	355,548	265,041
6	211,373	156,910
7	126,006	92,885
8	75,460	54,975
9	45,531	32,528
10	27,810	19,238
11	17,317	11,368
12	11,104	6,708
13	7,425	3,949

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Table 6: Descriptions of Influence Diagram nodes.

Node	Description	Node Type	State Space
D	Discovery results	Chance (C)	{success(s), failure(f)}
PC	Pre-clinical test results	C	{s , f, no result (nr) }
$P_1$	Phase 1 results	C	{s , f, nr }
$P_2$	Phase 2 results	C	{s , f, nr }
$P_3$	Phase 3 results	C	{s , f, nr }
FDA	FDA filing results	C	{s , f, nr }
PostApp	Post-approval results	C	{dog (d), below average (ba), average (a), above average (aa), breakthrough (bt)}
Real NCDR	Real Noncommercial discount rate	Deterministic (D)	{6%}
Real CDR	Real Commercial discount rate	Deterministic (D)	{9%}
I	Inflation	C	{3.18%, 4.00%, 4.20%}
NCDR	Noncommercial discount rate	D	
CDR	Commercial discount rate	D	
CF(D)	Discovery phase cashflow	D	
CF(PC)	Pre-clinical phase cashflow	D	
CF ( $P_1$ )	Phase 1 cashflow	D	
CF ( $P_2$ )	Phase 2 cashflow	D	
CF ( $P_3$ )	Phase 3 cashflow	D	
CF(FDA)	FDA filing phase cashflow	D	
CF(PostApp)	PostApproval phase cashflow	D	
NPV(Project)	Net present value of the project	Value(V)	

Table 7: Actual per-share values of Agouron stock and the valuations obtained through the Influence-Diagram, Binomial-Lattice and Decision-Tree methods. Values in parentheses are the differences in percent between the actual stock price and the price given by each valuation method. (The estimates for Binomial-Lattice and Decision-Tree methods are taken from Kellogg and Charnes[2000])

Date	Stock		Method				
	Price	Influence Diagram	Binomial	Decision Tree			
6/30/94	\$ 5.63	\$ 5.17	(-8.1)	\$ 4.51	(-19.8)	\$ 4.31	(-23.4)
10/20/94	5.63	6.56	(+16.6)	5.87	(+4.3)	\$ 5.70	(+1.4)
6/30/95	11.81	10.93	(-7.5)	8.51	(-27.9)	\$ 7.17	(-39.3)
6/30/96	19.50	13.61	(-30.2)	10.44	(-46.5)	\$ 10.26	(-47.4)
12/23/96	33.88	18.40	(-45.7)	15.45	(-54.4)	\$ 15.05	(-55.6)