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ANDREW LO: In today's lecture, I want to continue where we were last time in talking about applications of the net present value rule to capital budgeting and project financing. As promised, today what I'm going to do is to talk specifically about other alternatives to net present value that are not recommended, but which you need to know about simply because they actually are used in practice to some degree. And you have to be an intelligent consumer of all of these different ideas so that you can pick and choose.

And actually, there are some instances where these other alternatives can shed some light on the particular problem and challenges at hand. I'll try to describe those as we go over them.

Before I do, a student came up and asked me about a concept called adjusted present value. I wanted just to make a note of that because, so far, we've been talking about NPV. But in fact, both the textbook, as well as the best practices, would suggest that you use something called adjusted present value. Which basically makes adjustments for things like taxes, project interactions, strategic alternatives, optionality, and so on. I want to recommend that you first of all, keep in mind this notion of adjusted present value. That's what you'll be learning about in 402, and in more advanced courses on capital budgeting and project financing.

So for now, NPV is the right answer, but when you learn more about how to make those adjustments, you're going to want to use them, and then we call the particular criterion APV instead of NPF. Just terminology that you should be aware of.

All right, so what I want to do today, as I said, is to talk about three other approaches to capital budgeting that various professionals have used in the past, and which some are used to a great extent even today. And they are payback period and the discounted version of that called discounted payback. Second is the IRR, Internal Rate of Return, and the third is the profitability index.

Each of these have its own particular uses, and I'm going to try to describe them to you very briefly. And then we're going to talk about different applications. The bottom line, just to be sure that there's no misunderstanding, NPV is always the right thing to do. So that's what we're recommending for any capital budgeting application. However, you should still understand what these three other alternatives are so that you can speak about them

intelligently, talk about their advantages, and disadvantages.

All right, so let's get started. Payback period-- oh, question. Yeah?

AUDIENCE: Is this for [INAUDIBLE]? I mean you speak pretty firmly about NPV being better.

ANDREW LO: Yes. So is it people using those other methods are wrong, or less intelligent, or is there anyway to kindly describe that?

ANDREW LO: So the question is, why are they using these other alternatives? Let me get to that later, OK? I mean, one could argue that they're less intelligent. Not everybody is able to get into MIT and take this wonderful course. So by definition, they're less intelligent. But no, I don't want to make such a blanket statement.

I think that, partly, you'll find that these other techniques have been used in practice both because of cultural inertia. They were the first to have come on the scene before NOV was fully worked out. So people are just used to doing things the way they're used to doing it. People don't like change, necessarily, when it's particularly forced upon them.

But the second reason is that these other methods capture other aspects of risk that, in certain cases, may actually be more important for the particular individual decision makers. For example, we've talked about a lot of different kinds of risk. Market risk, estimation risk, credit risk. But what's the most important risk to all of you once you start working in your jobs?

AUDIENCE: [INAUDIBLE]

ANDREW LO: What?

AUDIENCE: [INAUDIBLE]

ANDREW LO: Exactly. Career risk. Career risk is probably the most important risk from the typical perspective of the decision maker. And frankly, some of these measures that I'm about to describe focus on career risk more than they do on the risk to the investor, or the shareholder. What I'd like you all to focus on in doing your jobs is to try to maximize the value of the company from the perspective of the owners of the company.

You are agents of the owners, so therefore, you want to maximize the value to the shareholders. But in fact, the way people behave is often somewhat different. So we'll talk about that as we describe each of these measures.

In fact, let's talk about the first measure as a way to illustrate the point about career risk. Payback period is a very simple concept. It is simply the minimum number of years that it requires for a particular investment to pay back. So if you invest a million dollars in a project, and it's going to generate some revenues, the question is, how long is it going to take before the project earns a million dollars? Namely, it pays back the original investment.

So the definition, here, is simple. If you assume that cf1 through cfk are the cash flows to the project, and you invest a certain amount of cash, cf0, initially, then the question is, how long a period do you need so that the sum of the future cash flows exceeds the initial investment? What's the minimum number of periods for that to happen? And that minimum, k, is called the payback period.

Now, right away you see that there's a problem because we're adding cash flows in different periods. So I hope by now, when you look at an expression like that, it causes you great cognitive dissonance and pain to look at that. It's like adding pounds to yen. Remember we did that the first day of class, right? Three pounds plus 25 yen is what? I don't know.

So when you're adding these cash flows, it doesn't make sense because you're adding different units. But let's forget about that for now. Let's just look at the equation and try to divine what we mean from it. For independent projects, a criterion that you might construct using payback is to accept the project if k is less than or equal to some pre-specified threshold, t star. And for mutually exclusive projects, where you can only take one, pick the project that has the smallest payback period subject to that threshold t star.

That's the typical approach to using payback. Clearly, this is a relatively shortsighted approach. It doesn't take into account scale, how much money you're going to make from this. It doesn't take into account risk, other than the risk of not getting paid back. So it's a very, very narrow focus in terms of what it's trying to accomplish.

Now, we can try to fix this. And we can fix this by using discounted payback. So now at least, the cash flows are in the same units. So you can use discounted payback, but it still ignores the cash flows after the payback period.

So in particular, you can have a project that requires cash inflow today, that then generates a bunch of positive cash flows thereafter, but then after the payback period, in some future date, it generates tremendously negative cash flows. Either because of some kind of liabilities that it

incurs, or some other additional investments that it requires to keep it going. All of that stuff is ignored by payback.

So in particular, this can have a negative NPV, but you might still want to take it because it pays back in a relatively short period of time. That's a mistake. But you can understand how something like this ended up getting put into practice, right? Career risk. If you're a manager of a division, and your job when you were hired is to turn it around and make it profitable, then it's very important that you take on projects with short payback periods. But that's not necessarily in the best interests of the company, or of the investors, or even of yourself if the incentives have been properly calibrated.

In other words, if, as part of your compensation contract, they say, here, you get a bunch of stock in the company. We want you to maximize the value of the shareholders. Then what you ought to be doing is maximizing NPV. You're not supposed to be focusing on other aspects. But as a practical matter, people look at this. People want to know how long is it going to be before this thing pays back.

Now, I don't want to argue that it's completely irrational. Can anybody give me a rationale for why payback is actually a sensible thing to consider? Yeah, David?

AUDIENCE: The main thing that fueled this, in an NPV calculation, you're assuming that you know what cash flow's going to be way out in the future.

ANDREW LO: Yeah, exactly.

AUDIENCE: And if you have a big cash flow way out in the future end, there's so little certainty your career's attached to that--

ANDREW LO: That's right.

AUDIENCE: --you'd want to weight effort more towards a calculus and--

ANDREW LO: That's right. So apart from the career risk, which you mentioned, but I want to downplay that because I want to argue that it is possible for payback to add value to shareholders. Simply because there is an implicit recognition for those who use payback that it's really hard to estimate what's going to happen in the distant future. So if you've got a project that pays back sooner rather than later, that's probably better because there's less certainty about what's going to happen in the future.

Now there's a lot of if's in that statement, right? If really what you're concerned about is the growing uncertainty of the project, that ought to be reflected in the discount rates. So I'm not saying that you should ignore it. What I'm saying is that payback is not necessarily the best way of capturing it. Although I think we could acknowledge that it does serve a useful purpose in the sense that it is focusing your attention on the relatively recent periods of cash flows. But there may be better ways of taking care of that, if that's the issue.

A question or comment? Yeah?

AUDIENCE: Liquidity?

ANDREW LO: Yeah?

AUDIENCE: If you have a project that takes cash outflow up front, and then years and years out, it gives you a big cash inflow. From that time until the cash outflow, you get nothing?

ANDREW LO: Yeah.

AUDIENCE: That could even present some problems in finance.

ANDREW LO: That's right. So another aspect of payback is this liquidity issue. In other words, projects that pay back in a shorter period of time require less liquidity over longer horizons. However, once again I'm going to say, if liquidity is the issue, you ought to take that into account explicitly, and understand what the term structure of your borrowing costs are over different periods. If you factor that in, then it should already be in there. If.

AUDIENCE: Is that closer to a discount rate or something--

ANDREW LO: That's right, it can. It should certainly, because we know that there is a yield curve. The typical yield curve is upward sloping. Typical I say, not always. But the typical yield curve is upward sloping. What that's telling you is that there's a premium for borrowing longer. So that basically gets at your liquidity issue. But if you have additional concerns above and beyond that, that should be reflected in your calculations. Payback is an inefficient way of capturing that. It's a very zero-one kind of an approach to dealing with that kind of an issue.

Yeah?

AUDIENCE: Think that people they lose the payback when they believe that the cash flow is the same all

over the period. Which really makes sense. Like in multiple.

ANDREW LO: So you're saying that it doesn't make sense.

AUDIENCE: It makes sense, when the cash flow will be the same--

ANDREW LO: If the cash, yes, that's right. If the cash flow is going to be level, then it makes sense. You're right.

AUDIENCE: Like multiple. You have a multiple for industry, you use it and you have it.

ANDREW LO: That's right, that's right. There are conditions under which payback can give you sensible results. But think about how restrictive those conditions are. You need to have level cash flows, and moreover, you have to be comparing projects, all of whom have level cash flows and have comparable risks. If they have different risks, or different levels of cash flows, or different liquidity, all of those things, cannot be captured by payback.

So I don't want to beat up too much on it. This is a relatively easy target. The point is that it provides some information, and you should know what it is. Regardless of whether you're going to use it. You ought to be able to have that at your fingertips so when somebody says, and undoubtedly somebody will say to you, when you're pushing a project, they're going to say, what's the payback period.

You need to know the answer. It's not good enough for you to say, my 401 professor told me it doesn't make sense. You've got to basically have an answer, and then argue that while payback doesn't summarize all of the characteristics that we're concerned about.

Second method, the profitability index. Now this one is another easy criterion to criticize, but it's so close to NPV that the only thing that really is an issue is the scale factor. So let me explain. Profitability index is simply the gross present value, as opposed to net present value. It's the gross present value, divided by the initial investment.

So the present value is simply the present value of all the cash flows, divided by the initial investment. So you could think of it as a gross rate of return. In other words, 1 plus the net rate of return of your investment in this project.

If the profitability index is greater than 1, take the project. If it's less than 1, don't take the project. And if you've got a bunch of mutually exclusive projects, pick the one that has the

highest profitability index. That's the approach. Now what's wrong with this? It's not that far off from NPV.

In fact, you could show that with a profitability index is greater than 1, you've got a positive NPV project. When the profitability index is less than 1, you've got a negative NPV project. So in terms of taking or not taking a project, it's actually the same as NPV. [INAUDIBLE]?

AUDIENCE: The thing it doesn't tell you is how much they usually must have [INAUDIBLE]. It can be $1 or $1 billion.

ANDREW LO: That's right, exactly. There's nothing that tells you about scale. So, if you guys give me $1 and I give you back $2, that's going to have a profitability index of 2. Which is going to look really good relative to an investment in Berkshire Hathaway 20 years ago, because that may not have given you the same profitability index. But Warren Buffett has made a lot more money than just a dollar.

So, this ignores scale and that's obviously something that you can't afford to do when you've got mutually exclusive projects where you're ranking them. You don't want to pick the one with the highest profitability index. What you want to do is to pick the one that is generating the most value for you, in terms of dollars and cents. In other words, NPV. So once again, NPV, although is very close to this, is actually preferred because you're actually getting a hard amount of dollars and cents as the bottom line.

Any questions about profitability index? Yes?

AUDIENCE: A lot of time, the money that you have in hand investment is limited. [INAUDIBLE] play into a role like when you have projects.

ANDREW LO: Well, it does play a role. So the question is, if you have a limited amount of money to invest, does that play a role? It absolutely does play a role, but it plays a role that is contrary to what the profitability index wants to do for you. The profitability index is simply telling you whether something is a positive or negative NPV. It's not telling you how much NPV you're going to get for the amount of money you're going to invest.

So what you need to do is to focus on the latter. In other words, how much cash are you going to be able to generate from a particular project? $50, or $50 million? That really makes a big difference. Particularly, if what you have is a limited amount of cash, scale is actually an important concept to you.

The reason that economists and financial economists, by extension, focus on rates of return? Did that ever strike you as being rather odd? In other words, when you talk to business people, very often they'll speak in terms of dollar amounts. Like, a startup costs $15 million, or the profits for last quarter was a million and a half dollars.

They won't talk always in rates of return. Whereas economists, particularly financial economists, they express everything in rates of return. I mean, that's what we've done in this course. We've spent most of our time focusing on r, not on v. v for value, r for return. Anybody know why that is? Yeah?

AUDIENCE: We always look about opportunity that we miss so maybe we can change the direction of our money [INAUDIBLE].

ANDREW LO: Well, that's true. But why focus on return as opposed to dollars? I mean, if we're thinking about changing the direction of our portfolio, you might think about investing, instead of a hundred thousand dollars in high tech stocks, take that money and invest a hundred thousand dollars in manufacturing. It's still about dollars and cents, isn't it? When you think about your portfolio, at some point, you've got to look at how much money do you have, how much money did you have, and is the current greater than the latter. You want to know whether or not you've made money.

Why the focus on r in this course? Yeah, Zeke?

AUDIENCE: Could be to get rid of the units.

ANDREW LO: I know, it is to get rid of units. But why do we want to get rid of the units?

AUDIENCE: Compared to their numbers?

ANDREW LO: But wait a minute. Why can't you compare dollars to dollars? I mean, you're right that you can compare a 3% increase in General Motors to a 2% decline in Microsoft. But you could also compare a hundred thousand dollar increase in your portfolio in General Motors, versus a $50,000 loss in Microsoft.

Yeah, Courtney?

AUDIENCE: It goes back to scale because it's a $50,000 [INAUDIBLE] for that company, but it could be your entire company's profit. So it shows a return on an individualized basis.

ANDREW LO: It shows the return on an individualized basis, and it gets rid of the scale. That's true. So you're able to compare the scale for different companies, but what's wrong with using dollars to do that? I mean, if you're an investor. So from the investor's perspective, if you're looking at an investment in General Electric versus Microsoft, wouldn't dollars make more sense? Rather than returns? Because you can still compare them, right? Yeah?

AUDIENCE: If you're going to invest x amount in both companies, it might create a greater impact on one. And you want to see where your money is going to be or--

ANDREW LO: OK, you're on the right idea. You have the right elements, but you haven't put it together. It's true that scale is the issue, so you've got your finger on the right concept. But what about scale is the issue here? [INAUDIBLE]?

AUDIENCE: I think you want to develop a theory that says [INAUDIBLE], that basically you can tell them what's your return in terms of percentages and then they can decide I want to invest $100, I want to invest a million dollars.

ANDREW LO: Good. So that's following in Courtney's point that we want to develop a theory that suits all investors, so it's not focused on scale. But implicit in not focusing on scale, we're making another assumption. What are we assuming?

Mike?

AUDIENCE: In terms of focusing on the marginal dollar, you should actually take the highest return. If someone's going to triple that $3 investment, you should at least put your first $3 in that. Give them bang for your buck. And then go down until you're getting to a lower marginal return on larger investments.

ANDREW LO: And why should you do that? Why should you go down the line in that manner?

AUDIENCE: Because that will maximize your overall return.

ANDREW LO: But wait a minute. I thought that if we put our money across all of these various different projects in proportion to the standard portfolio theory, the tangency portfolio, we get the biggest bang per unit risk. So, are you saying we ought to deviate from that? What about the theory that we developed requires us to focus on returns, rather than on dollars invested.

You've all been very patient in not bringing up this issue. You've just taken it as given that I'm telling you the truth about focusing on returns. Why not focus on the actual dollars that you invest? Remy.

AUDIENCE: Focusing on return is the easiest way to weigh it versus the risk.

ANDREW LO: That's true, it does make it easy to weigh it against the risk. But in the end, don't you care about what your dollars at risk are?

AUDIENCE: You can't check out what it is on the tangency portfolio.

ANDREW LO: Well, I could rewrite the tangency portfolio in terms of dollars, instead of return.

AUDIENCE: You don't want to do that.

ANDREW LO: I don't want to do that, you're right. Why don't I want to do that? Aside from the fact that the fonts are not going to fit on that axis. Well you're on the right track. All of you. I think you sense what I'm getting at, but you haven't put your finger on it. Let me tie it all together, and tell you where you're getting, because I think that we're going to get there eventually.

The idea is that we want to come up with a framework that applies to all investors. That's true. And so, it would be really convenient for us to be able to use returns and units of risk so that whatever dollars you have, you can simply apply the theory and find out where you are on that frontier. And just simply multiply by the initial amount of wealth to figure out all your dollar investments.

Underlying that approach is a belief. And here's the belief. The belief is that we can invest however much money we want, and get these kind of returns. That's the key that all of you are groping at. Implicitly, I think you understood this, but you haven't articulated it. What we're assuming, when we put down all these equations in returns, is that scale doesn't matter in the sense that no matter whether we're investing a hundred dollars, or a hundred million dollars, or a hundred billion dollars. We're going to get the same returns.

And the fact of the matter is that's just not true. Scale absolutely does matter. It matters because the more money you put into certain kinds of investments, the harder it will be for those investments to maintain the same level of return.

Now, that has a very different impact among different industries and among different

investments. For example, right now, nanotechnology is just beginning to take off. And so, if you end up putting a couple of extra billion dollars in nanotechnology, it's unlikely you're going to really affect the returns because the technology is still emerging. But if you take a very highly capacity constrained strategy and try to implement that same idea, you're going to have a very hard time doing it.

If you decide that you want to focus on middle level software for dealing with file server control mechanisms, it's a relatively narrow sector in the technology sector. And you want to put $2 billion of extra money in that sector this month. Good luck. You'll have a very hard time doing it. Not to say that people won't take the money. I'm sure you can find people, yeah, sure give me the money. But they're not going to be able to produce the returns that you would expect from that very narrow slice of the economy.

So all of what we've done in this course ignores scale from the perspective of risk and reward, but the one area where scale absolutely matters is NPV. In other words, when you're a project manager trying to figure out should I take Project A, or take Project B, scale matters. As Dee pointed out, in certain cases, you don't have more money to put into a particular project. In other cases, you have too much money that is not suitable for a certain project.

But the bottom line in both cases is NPV. Dollars. Actual dollars and cents. That's what you want to focus on from the perspective of capital budgeting or corporate finance. Mike?

AUDIENCE: If the NPV is really, really good, and the return is good, you should go get more capital--

ANDREW LO: That's right, that's right. If the NPV is really, really good, first of all, you're going to take the project. But secondly, what you're going to do is you're going to try to figure how to scale the heck out of the project and take as much of it as you want. Why? Because more money is preferred to less money. Simple as that. And again, anybody that violates that, see me after class. Be happy to help you. Yeah?

AUDIENCE: If you did that it would go back to your--

ANDREW LO: Exactly, it would.

AUDIENCE: Or, it would change r.

ANDREW LO: It would change r, that's the point. That's why you shouldn't focus on r from the perspective of capital budgeting. From an investor's point of view, from a point of view of you and me,

investing in the market, we're not going to affect r. I mean, I hate to depress all of you, but most of you, if you put your entire wealth into the market, you probably won't move the market by a whole lot.

That's not true of everybody, and it's not true of all assets. But it's certainly true of the market as a whole. In other words, if we put all of our collective wealth into the S&P 500, we're not going to move it by a lot. But if you're a corporation, and you put all of your corporate wealth in one particular division of the particular company you're in, that could have dramatic consequences for the rate of return for that project.

So scale matters for capital budgeting. It doesn't matter if you're thinking about each of us as a small investor. And so what I derived for you in the capital asset pricing model is a derivation that assumes each of us is small. We're not going to affect prices, or therefore, returns. And so, we can take returns as given. In other words, whether we're investing $100,000, or $200,000, or $15,000, or even a million, the analytics that derived are pretty reasonable approximations. That's very different from evaluating a particular investment opportunity for a division of a corporation. That's not the stock market. We use the stock market as a guide for computing the discount rate.

But the bottom line analysis is how much of the investment can be supported by what you want to put into it. And as long as the NPV is looking good, you want to keep doing it. And to Remy's point, the more you do it, most likely, the less NPV will come out, eventually. And you're going to drive the thing into the ground in the sense that you're going to keep doing it until it stops being profitable. That's only human, it's only natural, it's only good business to drive it into the ground.

Which is, by the way, what we did in the subprime mortgage market, right? That's why we're in the current crisis we're in. We basically drove that business into the ground and then some. But it's a natural phenomenon of business practice to constantly be coming up with new ideas. The ones that work well, we're going to keep on implementing them. We give them more capital until they start declining in their rates of return, then we take capital away. For the next year or so, we're going to be taking capital away from the real estate markets.

Any questions about scale? That was a bit of a digression, but a useful one, in the sense that NPV is the right thing to do because it doesn't ignore scale. Whereas, for the small investor, ignoring scale makes perfect sense. Because then we are able to derive a theory that applies

to most everybody. By the way, that theory doesn't apply to some of the largest investors today.

For example, certain sovereign wealth funds, certain public pension funds, they can't invest according to the basics of portfolio theory. Because when they put money to work, they're looking to put a couple of billion dollars to work in a single investment. It's not worth their time to try to figure out how to allocate $5 million here, $10 million here, $20 million there. There's not enough hours in the day when they're managing a $250 billion portfolio to be able to do that.

And so, when you're a large, large investor, the theory that we developed here in this class, it doesn't apply. You need to take 15 433 to understand how to deal with the issue of price impact and large scale investments. Fortunately, or unfortunately, that won't be a problem for most of us, so you have to keep that in mind. For most of us, the theory of investments that we developed in this class is perfectly appropriate. Except when we're talking about NPV. Yeah?

AUDIENCE: Because of this lecture, will there be any indices or variables that we can use to determine the part of the initial returns for those sort of cash flows?

ANDREW LO: In this particular context, no. You're going to learn about that in 402, as well as in 434, and some of the more advanced courses on capital budgeting. On how to scale an investment. But the basic principle, you, I think, already know because you've taken microeconomics. The basic principle of how much to invest is not to invest until you start losing money. That's actually typically how it's done in practice. That's not necessarily the best way of approaching it.

According to an economist, the best way to invest is until the point at which the marginal benefits is actually equal to the marginal cost of the investment. So when you're trying to maximize profits, you're asking how much money should I invest in a particular division. You ought to keep investing until the point where the marginal benefit is equated to the marginal cost. In other words, where the profit maximizing point is, is where the marginal revenue is equated to the marginal cost of investment. That's true for any kind of an investment.

The point is to be able to measure those things accurately enough to find that point. We don't do that in this course because, again, we're assuming that you're relatively small relative to the grand scheme of the investment universe. But as you get bigger, you need to develop other techniques to be able to deal with that. And one is this marginal benefit, marginal cost

approximation.

Other questions? So that's the profitability index. I just give you a couple of examples, so you can take a look at them at your leisure. It's pretty straightforward.

All right. Now, let me talk about the last, and probably most important, alternative to NPV. This is something that's actually used in practice pretty commonly, and there are certain areas where it's used almost exclusively. So it's a very important idea that I want to go over in detail.

The idea behind the IRR looks simple enough on the surface of it. And those of you who remember back to the lectures that we did on bond mathematics, you'll recognize the IRR as nothing more than the yield to maturity of a bond. So if you pretend that this is like a bond, where i sub 0 is the market price of the bond, and the cf1 to cft are the coupons and principle payment of the bond, then the internal rate of return is nothing more than the yield to maturity of that bond. That's mathematically, formally what it is.

But it's got a different interpretation here. The interpretation is that i sub 0 is the amount of money you're paying for this project. And cf1 through cft are the cash flows you're getting from the project. And the IRR is that yield, or that rate of return, such that it makes the project break-even. In other words, the present value of the future cash flows is actually equal to the amount of investment that you put into it at that IRR rate of return.

Any questions about that definition?

Now implicit in that definition are a couple of hidden assumptions that makes this work. One assumption is that the only investment that you're going to make in the project is upfront. You're going to pay i sub 0, and you're not going to pay anything more for that project. It requires no more cash inflows from you, the investor.

The second assumption, which I guess is sort of the same as the first, is that all the cash flows are non-negative. They're either 0 or positive. You don't have any future negative cash flows. So once you invest in your certain amount today, then thereafter, you simply collect money from the project that comes in over t periods.

If those two assumptions are satisfied, then this may be a reasonable approach. So just to be explicit, the way that IRR is used is for independent projects. Accept a project if the IRR's greater than some hurdle rate, some IRR star. You can think of that as your internal, or your

required rate of return. So as long as the break-even IRR is equal to, or greater than that threshold, then you're OK.

Second, if you've got mutually exclusive projects, then you pick the one that has the highest IRR.

Yeah, [INAUDIBLE]?

AUDIENCE: [INAUDIBLE] You could have an outflow in the first year, and you could have an increase [INAUDIBLE]

ANDREW LO: I'll show you in a minute why you need that assumption, those two assumptions. In fact, when people use IRR, they don't bother with any assumptions. They just compute it. So the assumption is to give them the benefit of the doubt. I want to come up with conditions under which it might actually make sense to use this, and those are the conditions.

But for now, let's forget about all conditions. And let me tell you what the problems are with IRR. There are certain situations where using IRR will lead to the same decisions as NPV, and there they are.

There's only one cash outflow, which occurs at time 0. There's only one project under consideration, so you have multiple projects that you're comparing. Third, the opportunity cost of capital is the same for all periods. And the threshold rate that you use is set equal to the opportunity cost of capital. Now, the reason that you need all of these. I'm going to show you by way of counterexamples. But let me just tell you right now, up front, what the shortcomings are of IRR. Why you might want to think twice before using it.

One is that in certain cases, the IRR may not exist. And in other cases, you may have multiple IRRs. I'm going to show you in a minute. Second, you're going to get incorrect rankings for IRRs where you're looking at loans, loans meaning you've got a negative cash flow starting today, and then positive cash flows tomorrow-- Excuse me. You have a positive cash inflow today, and negative cash going out tomorrow and the day after. Like a mortgage.

A mortgage, you get money up front, and you're paying money out later on. If you do that, then you've actually got to flip around the ranking and take projects or loans with smaller IRRs, not higher IRRs. And finally, it also ignores scale because it's a rate of return. It doesn't look at dollars and cents. Zeke?

AUDIENCE: I have no professional experience but there's something that simply bothers me. You told that for, example, that this model doesn't work if you have negative cash flows and that people can make mistakes and use negative cash flows in real life. How does this happen? Don't people have-- in this Excel sheet, it's a simple calculation. How is this allowed in professional--

ANDREW LO: Hold on for one second, let me show you. I'm going to show you by example. It's not as easy as you think. Let me give you some examples for incorrect rankings. This is one example where, as I said, with a loan you want to pick the project that's got a lower IRR, not a higher IRR. So that's one issue. But let me give you an idea of the nonexistence of an IRR.

Project one has two negative cash flows. One in the first period, and another one in period two. Project two has only one negative cash flow, but it happens in period one, not in period zero or in period two. Both of these projects are not particularly weird. I know it's true that they don't have negative cash flows on day one and positive thereafter. But I don't think you would look at these and say that, gee this is really pathological, or perverse, in any way. It's just a different way of structuring your particular financing, or your cash flows.

It turns out that in both of these cases, the IRR doesn't actually exist. Now by exist, what do I mean? Let's go back and look at exactly how to compute IRR. To compute an IRR, you have to find a number that satisfies this equation. And so with k period IRR calculation, we've got k cash flows over k years. What, in the end, are you trying to solve? What kind of an equation? Nobody on high school math teams? Andy?

AUDIENCE: kth order polynomial.

ANDREW LO: Yeah, a kth order polynomial. You all know what that is, I hope. Right? Second order polynomial's a quadratic. ax squared plus bx plus c equals 0. A third order polynomial has a cubed term, and so on. A kth order polynomial has powers of IRR that are up to order k.

Anybody tell me how many solutions there are of a kth order polynomial?

AUDIENCE: k [INAUDIBLE]

ANDREW LO: Up to k solutions. Do you always have solutions?

AUDIENCE: No. k is obvious.

ANDREW LO: We're getting some different theories now. So some says yes, some says no, some says

where k is odd. By odd I presume you mean not even, as opposed to weird, right? it actually turns out that you can construct a solution for every single kth order polynomial. But that's if you change the definition of what you mean by a solution. Right, exactly.

If you introduce a new set of numbers called complex number, by that I mean numbers where the square root of negative 1 makes sense. If you will extend the number system to include these weird things called complex numbers, then it turns out that all polynomials, all kth order polynomials have exactly k solutions. How nice. The problem is that these solutions can involve complex numbers. And as far as we know, complex numbers don't have any ready interpretation in terms of interest and money.

So in other words, the only solutions that matter for you and me, for practical purposes, is what are called real solutions. And in particular, not only do they have to be real, but it would sort of be nice if they were positive numbers. Because interest rates, again, although they can be negative, it's kind of hard to imagine what that implies over long periods of time.

So when I say that a solution doesn't exist for these two cases, I don't mean that they don't exist, exist. Of course they exist, they have to exist. The problem is that the solutions-- these are two period cash flows. So we're talking about quadratics. We all know the solution to the quadratic equation of ax squared plus bx plus c equals 0. What's the solution? Anyway tell me quickly? Negative b plus or minus the square root of b squared minus 4ac over 2a. Remember that?

It turns out that you don't get real solutions all the time. Meaning that, in certain cases, that formula will produce solutions that have the square root of negative 1 in there. And that makes no sense from an economic perspective. It just so happens that in these two cases, you should go home and try it, and you'll see for yourself. When you come up with the two solutions that exist for both of these cases, they're complex numbers. So I challenge you to tell me what the right investment decision is by looking at those complex numbers. It can't be done.

Which means that IRR doesn't always work. And here are two relatively reasonable examples that nobody should be expected to look at and say, ha, of course. You can't use IRR here. These are real life examples. And by the way, this is just two periods. If I had five periods, and I had some positives, some negatives, it gets even more complicated.

So even within a spreadsheet, where you can see the positives and the negatives, and you

can compute IRR-- you can do this in Excel. And you should do that. You'll get these weird symbols that come up, that will start spitting up blood and say that it can't handle this. Unfortunately, if you did it MATLAB, which I know a number of you are likely to do, you will get an answer. MATLAB has no problem with complex numbers.

So that's one problem. Let me illustrate to you though, where the problem comes with multiplicity of solutions. So this is a graph of the polynomial. In this case, the third order polynomial. And so what I'm doing is I'm calculating the NPV of project 1 and of project 2 as a function of the underlying interest rate. And an IRR corresponds to a situation where the NPV is equal to 0, the break-even point. What you'll notice is that the 0's are where this curve intersects the y-axis, or the x-axis, sorry. And so with the first project, you actually get a unique solution. It only crosses the x-axis once. So you get a unique, real solution.

But if you take a look at project 2, project 2 crosses the x-axis once, twice, three times. You get three solutions. They're all real, by the way. You get three, real solutions. Which one would you like? Take your pick. You pick the biggest one? Or the smallest one? Or maybe average them, or do something? I don't know. The problem is that with IRR, If the pattern of cash flows is anything but strictly positive, you get weird results.

Now, I told you before that IRR is used almost exclusively in one particular sector, one particular segment, of the financial industry. Anybody know what that is?

AUDIENCE: Bonds?

ANDREW LO: Bond? Well, that would be a good answer, you're right. Yield to maturity is what IRR is in bonds. That wasn't what I was thinking about, but you're absolutely right. IRR, in fact, is used all the time in bonds because you quote yield to maturity. And it's not surprising because with bonds, you only have positive cash flows, and you only have an initial payment upfront, which is the price of the bond. So all of the criteria that I required in order to make IRR equivalent to NPV holds for bonds.

But I'm thinking about something else. What other part of the financial industry uses IRR as a way of making investments? And not only that, but of quoting performance. What's that?

AUDIENCE: Private equity?

ANDREW LO: Private equity, exactly. Private equity. In private equity, almost every venture capitalist will tell

you what their IRR is of their portfolio. And there are a couple of reasons for this practice. One of course, is that for most private equity ventures, it is all about cash up front, and then positive cash flows thereafter. Unless of course, you require additional financing like mezzanine financing. In which case, now you have a hard time using IRR for the whole thing.

You could use IRR for the separate tranches of investments, and again, that's kind of an accommodation. It's a fix for trying to deal with the weaknesses of IRR. If you focus just on the particular tranche of an investment, you've got a tranche of investment going in, cash flows going out, and it all satisfies the NPV criterion.

But the other reason for focusing on IRR is because, again, this is an issue of scale. You want to compare two investments, and they may require different dollar amounts, so you'd like to be able to compare their performance in some way that doesn't include the scale. Because you want to be able to compare across a bunch of different investments and see how each manager is doing per unit dollar invested.

However, the bottom line of a venture capitalist is, I've got a billion dollars to invest. I have to figure out where to put my money. I can't afford to put my money in smaller investments that are not going to give me the kind of return that I need to have. So in the end, a venture capitalist is going to have to look at scale anyway.

But for historical and cultural reasons, you actually have the venture capital community the only one that really focuses almost exclusively on using IRR. And for their applications, like the bond pricing example, it's generally OK, but it may not be. And so you should understand those conditions under which it may not be. So I want you to refer to these, and if you have a moment during your holiday break and you're bored, you might want to run a few of these in Excel. Just literally try to compute the appropriate IRR in Excel. And just prove to yourself that you can't, that you get some weird results out of that.

Any questions about IRR?

By the way, again, there are no formulas other than the quadratic for how to compute it. So in most cases when you want to compute IRR, you have to use numerical methods. You have to basically solve a non-linear equation for a 0. So effectively, you have to do this. You have to find the 0's of these equations. That could be a little bit of an exercise to do that.

There are other examples here where I try to come up with ways to fix IRR, maybe by looking

at incremental cash flows, or looking at different ranking methods. But the bottom line is use NPV. Be aware of how to compute an IRR, but you should understand that IRR, in the cases where it matters, either it agrees with NPV or it doesn't. And if it doesn't, you can't use it because it's going to create all sorts of contradictions and weird results.

I want to conclude this lecture on capital budgeting by talking about what people actually do in practice, and give you a little bit of a preview about what you're going to learn in 402 as well as in 434 and other courses on corporate financing and capital budgeting.

Right now, as of maybe five years ago when this survey was done, for large US firms, believe it or not, payback period was probably the most popular. It's the one that people focused on the most. Again, not necessarily exclusively. So it could well be that people use payback period as one criterion, but they use many others as well. But over 80% of the companies surveyed use payback period.

65% use IRR, which is quite a lot. But again, a significant fraction of that is private equity. And by the way, for non-financial corporations that have private equity operations within it, for example, General Motors has a part of their pension fund devoted to private equity investments. They will use IRR as well, because other venture capitalists use that.

NPV is actually gaining ground. So it's now more popular than IRR. If you surveyed multinationals and US corporations 20 years ago, it would have been flipped around. IRR would have been way more popular than NPV, but that's changed a lot just in the last 20 years. However, when you look at multinationals, you see that actually, IRR is still more popular. So that's something to keep in mind.

When you're dealing with foreign companies, they may be looking at investments from a VC perspective, as opposed to from a pure net cash flow NPV perspective. So that's something that you'll want to be wary of. And by the way, that's probably one area where you can make real progress in terms of an impact through your careers.

Historical comparison, this gives you a little bit of a time series of how things have changed over time. So back in 1959, payback period, IRR, was quite a bit more popular. Over time, that's declined, and over time, IRR has gained more ground. But NPV, as of 1981, was lagging far behind. And within the last 20 years, we see this chart where NPV has caught up a great deal.

A large part of that, if you want to know where that came from, a large part of that was thanks to Brealey and Myers. The textbook that you're using now was probably the first major corporate finance textbook ever written, way back in the 1980s. And Stu Myers and Dick Brealey wrote the book really because there was nothing else that was out there that corresponded to these kind of modern finance principles. And so Stu and Dick have a lot to do with these numbers as of today.

Other issues that we were not able to take on in this course, but which you will see in 402 and 434, is how to deal with other aspects of the capital budgeting process. For example, competitive response. When we think about making investments in projects, we are assuming everything else as given. This is sort of like putting money in a stock market. When you put your money in the stock market, you're assuming that the means and the variances are given. That your investment has no impact on the market as a whole.

For specific kinds of projects, that's not true at all. The perfect market's assumption that we make from the perspective of a small investor investing in the entire market, those set of assumptions don't work for you making a decision about whether to invest in a new technology in your particular industry. Because most likely, that new technology will have a very significant impact on that industry if it's any good. So therefore, you're going to have to deal with competitors and the competitive response. Things are going to change because of the way you make your investments. So that's something you'll have to take into account.

Capital rationing, which means you don't have all the money in the world. There's a limit to how much money you can invest, so now, given that there are limits to how much money you have, you've got to pick your opportunities more carefully. And some of these capital rationing requirements are implemented over multi-year periods. So for example, you might have a three year budget of $100 million to make investments in new technology. Over three years, you can use up to $100 million.

So now, not only do you have to think about how to spread your money over opportunities this year, you've got to think about a spread it out over a three year period. And you have to think about spreading it out to projects that you don't even know exist right now.

So the problems, the challenges, become much, much more complex as you start making the assumptions more realistic. You've got now, the very basics to understand how to do this for the very, very simple cases. But the more advanced courses will, one by one, relax these

assumptions and give you more tools to be able to handle more complex situations.

The examples that I give in this slide are looking at short run versus the long run, as well as dealing with general noise. In other words, you may be taking in lots of data, not all of that data is equally meaningful. So you need to know what to ignore, and what to focus on. That will be part of those challenges. You'll get that in 402, and more in 434.

So to summarize, we are now done with pretty much all of the finance theory that we need to value and to make decisions on virtually any kind of investment that's out there. The key points for capital budgeting is use NPV, or in the case of more advanced kinds of concepts, APV. Take all projects that are positive NPV, and if they're mutually exclusive, take the one with the biggest NPV.

Consider project interactions separately. So consider the project on a standalone basis, then consider any interaction effects that may or may not exist. You can evaluate them separately, and add them together at the end. Use after tax cash flows for the NPV calculations, not accounting earnings. And when you need discount rate, use the capital asset pricing model. The capital asset pricing model provides you with a risk adjustment for the required rate of return.

And be wary about risks that change over time. So every single year you use your cost of capital, make sure you can justify the particular risk associated with that year. Remember the example of drilling for oil and how the risks change dramatically as you go from oil exploration to oil production. Those are two different activities.

Finally, think about all the other alternatives to NPV. And you don't have to be a snob about it. Don't tell people, NPV's the only way to go. It's either my way or the highway. You recognize that there are other elements of risk and reward that may be captured by payback, by internal rate of return, by the profitability index. But in the end, what you're going to want to base your decision on is primarily NPV considerations, with these other factors thrown in as well.

I'll conclude with one last comment about capital budgeting, which is something that is completely outside the purview of this course, but it's not outside the purview of your MBA. And that is that why I've been talking about for the exclusion of everything else in this course is the economic and financial considerations.

Obviously, when you're engaged in trying to get a project approved, or making a decision on a

project, there are many other considerations that you should not forget about. Considerations like political, social, cultural, implementation, all sorts of practical aspects that you need to put together. And so all of the other courses that you've been taking are designed to try to get you to think about that.

But unfortunately, or maybe inevitably, in a curriculum like the MBA, we pick apart all of the various aspects of a decision and then study it to death, and try to come up with the very best possible approaches for each of those particular silos. It's your job, ultimately, to put all of that together. And you will do that, you will be asked to do that, whether you know it or not, when you start working.

So what I've been focused on exclusively is the financial and economic considerations. And I believe you now have the tools to be able to analyze any project, at least to get a starting point for an intellectually consistent way of looking at it. But don't for a moment think that those are the only things that are important. The political, social, cultural ramifications are going to be extraordinarily critical, and only you will be able to figure out how to put that all together.

So hopefully in this particular course, you've learned something valuable from that one aspect. But just keep in mind, it is only one aspect, one perspective. And there are others that you will have to incorporate into your way of thinking.

That's it for capital budgeting. Any final questions before we move on to the final lecture of this course? Yes?

AUDIENCE: I just have one small question on IRR again. In the examples you showed, the cash flows in the out years and years [INAUDIBLE] were more, they were the opposite direction from the initial year cash flow, but greater than the [INAUDIBLE] cash flow. Does it matter that that's not the case that can happen?

ANDREW LO: Well, I guess the answer is, it depends. In other words, what you detected was not a universal pattern that can be systematized and then incorporated into IRR. In other words, if I had a longer period of time to be able to play with changes of sine and changes of magnitude, I can get any kind of pattern that you want. For example, in the dotted line curve, I can have this curve flip around the other way so that it starts negative, goes positive, and it goes up like that. Just by changing the sign patterns to something else. If I had a quartic term in there, I can make it even more complicated.

So the longer the number of periods, the more number of periods that I have to play with, the more patterns that you can create so that it would be really impossible to reduce it to a systematic set other than this proscription here. If these four conditions are satisfied, then you're OK with using this as opposed to NPV. But that's the only simple case where you can say something meaningful.

By the way, the number of 0's and the nature of the 0's of polynomials, that turns out to be related to a very, very, very famous and hard unsolved problem in mathematics known as the Riemann zeta hypothesis. We're not going to talk about that in this class, unfortunately. It is beyond the scope of the school.

But I just want to let you know that there is something inherently extraordinarily deep about the underlying contradictions that get generated by IRR. You don't have to solve the Riemann zeta hypothesis to understand it, but you can get very, very complex, very quickly by looking at these kinds of patterns.

In fact, it would be bad news for us if these patterns actually mattered for investing. The fact is they don't. The bottom line is NPV. How much money are you generating from this investment, period. And if you focus on that, you're not likely to make a lot of mistakes. But you should at least be aware about these other techniques. So that's why I went over them.

Yeah, David?

AUDIENCE: Can you talk a little bit more about social, political, and cultural risks. From the perspective of the CFO of a company for example, who has to make a decision on whether and where to invest. It makes sense that there will be some political implications that cannot be captured by every model. But if I'm a private investor and I invest in a company that is listed in a stock exchange, I would expect all these considerations to be captured already in the stock price.

ANDREW LO: Well, yes and no. Let me give you an example that is a somewhat controversial one. I don't really know the answer to it, but at least we can talk about it in the context of current events. If you take a look at what happened with Bear Stearns versus what happened with Lehman Brothers. It's kind of hard to understand why what happened, happened. Bear Stearns was deemed too big to fail. And so it was navigated to a soft landing with JP Morgan.

Lehman on the other hand, which in certain respects was even bigger and even more broadly intertwined in our financial system, was allowed to fail. I don't understand that from an

economic perspective. In fact, I'm not sure there is an economic perspective to why it failed.

But there may be a political dimension. For example, and again this is pure speculation, so asking me for my views on political elements, I'm happy to provide. But it's like asking Roger Federer what he thinks about the S&P 500. Not that I'm Roger Federer, but it's asking somebody who's a professional in one area what they think about something else. I'm not sure it's a good idea.

But the point is that my conjecture is that the reason Lehman Brothers was left to fail was because there was so much criticism and backlash from the Bear Stearns event that both Treasury and the Federal Reserve thought that it was politically untenable for them to do it again. Because if they did it again, then they would be expected to do it again, and again, and again, and again. In which case, all the firms would be in line to try to get a bailout. And they are.

However, to highlight the complexity, to highlight the complexity of the political dimension, now that Lehman did fail and it caused such disastrous consequences, now maybe it's truly impossible to let any company fail. Because people will say, oh you remember Lehman Brothers and what happened there? You better not do that again.

So I don't know the answer to the question about what the political landscape is going to look like a year from now, or even six months from now. So I don't know whether or not it's significant in terms of what will happen, but surely in the past, politics has played a very big role, even for private investors.

But that actually wasn't the politics I was talking about. That certainly matters a great deal now, but the kind of politics I was talking about was more within a company. So I'll give you an example. You're a new division manager that was specifically hired by the CEO to turn around a division. And in your first quarter on the job, you propose a very specific restructuring for that division. Chances are the CEO is going to agree with you. Knowing nothing about whether the proposal is smart, or stupid, or good, or bad, most likely, the CEO's going to agree with you.

Why is that? You know why, right? You guys agree with me. If you agree with me, that means that you understand something about the political situation that has nothing to do with P&L, nothing to do with NPV, nothing to do with cost of capital or risk adjustment. Somebody just hired you to do a job and they're going to have to give you the benefit of the doubt for a little while before they can pull in the reins. That's what I mean by political considerations.

So when you're thinking about capital budgeting, you've got to factor in all of these considerations. Which is hard. It's what makes business both an art and a science. You need to have both of those elements represented. And I just wanted to bring that up to remind you not to forget about those elements. Economists have a very bad habit, myself included. We think that everything is economic. Someone said that to a person that owns a hammer, everything looks like a nail. And I agree.

As an economist, I have these tools that I think apply to everything. And there's a danger that as an economist, I see everything from the economic perspective. And it's only after you've been hit over the head with a bunch of failures of your theories that you'll begin to realize maybe there's something else out there that's explaining behavior. Which I'm going to talk about next.

But the traditional approach of economists is to assume that everybody is rational, everybody's maximizing NPV, the markets work efficiently. And by the way, if that's the case, then your job is really easy. What makes it hard, and I would argue fun and challenging, is all the other stuff that makes this stuff not work the way it's supposed to all the time. You have to know when to use these methods and when to use other methods in order to be able to advance your particular objectives. And ultimately, you have to understand exactly what kind of objectives you want to achieve.

So that's going to actually be the topic of the latter part of the next lecture, is objectives. I've told you up until now that the objective for most shareholders and most corporate managers is to maximize NPV. That is an approximation to a much more complex reality. So I'm about to change your view of that reality over the next lecture and a half.

Any other questions?

This concludes our lecture on capital budgeting, and what I want to turn to now is the last lecture of the course, which is efficient markets, lecture 21. I'm going to get started on this just very briefly today, because we're almost out of time. We've got about another 10 minutes or so.

I want to give you an overview of where we're going and why we're going to do this lecture. Typically, efficient markets is a lecture that is given in most corporate finance and Introductory finance courses at the beginning of the course. And the reason it's done at the beginning is

because actually, we need this efficient markets hypothesis to justify most of what I taught you over the last 13 weeks. Let me explain why that is.

For the longest time now in this course, I've kept repeating that when we need a discount rate, when we need a price, when we need a value, where do we go? To the market. All of you, right? And we did that. The first day of class, I auctioned off certain items and we engaged in price discovery. That's an enormous benefit, this wisdom of crowds that we relied on. And that's why at the very beginning of most of these finance courses, we typically teach our students to trust in the market. Now I didn't do that in this course because I don't want you to trust the market. I want you to learn from experience when to trust the market, and when not to.

But the fact of the matter is the theories that we rely on, this notion of risk adjustment, this cost of capital, this CAPM. All of that relies on people being rational. It relies on all of you in this room wanting to hold the tangency portfolio. It relies on supply equaling demand. And unless we have that kind of behavior, a lot of our results go out the window.

So I want to talk about the justification for that assumption in this particular lecture. I told you that I'm going to tie together all the various different loose strands of the course in this one lecture, and I do mean to do that. What I'm going to do is first of all, make an argument for why it is you ought to trust in market prices. Why the wisdom of crowds is very wise, most of the time.

But then I want to spend the bulk of this lecture telling you why it can break down. Now, I don't think I need to tell you that after the last 13 weeks. You've sort of seen that in real time. But I want to give you an understanding of what happened. And actually, I'm going to be able to provide you with a complete and satisfactory theory that makes sense of everything that has happened over the last 13 weeks. You may be skeptical about that, but I promise you, it will be true.

I have a theory, which is not generally accepted. So I've got to start with that disclaimer. This is a theory that I'm going to tell you that is my own pet theory, it's not in any textbook because it's relatively new. And if you do a search for it on the internet, my name was the only name that's going to come up. So that's both good and bad. You're hearing it from the horse's mouth, but it is a horse that's telling you this.

I'm going to start by first explaining to you what efficient markets is. I think you already know,

right? You can trust the market prices. The market price tells you what you need to know. And after I make that argument, I'm going to then turn around and take the other side of the debate, and give you all the reasons why people are irrational, silly, mistaken, stupid, all of the reasons that psychologists tell us markets are crazy, and you should never trust in market prices.

And then I'm going to try to bring together the two sides of the debate using some recent research from the cognitive neurosciences. So I'm going to actually talk a bit about the neurophysiology of the brain, and it turns out that that research is going to be directly relevant to how we interpret what's been going on over the last 13 weeks, over the last 130 years.

Let me start with that argument about efficient markets. Market efficiency says that there's no free lunch, there's no arbitrage, you don't get something for nothing, prices fully reflect all available information, and there's no way to make money in the marketplace. Active management does not add any value. Now, if you really believe this, why are you here? Why are you taking finance?

Well, it turns out that there is a reason for taking finance even if this is true, which is that finance is the language by which you conduct discussion and analysis in business negotiations. But even apart from this, I would argue that most of you are probably thinking you can beat the market if you work hard enough and if you're smart enough. That's not the perspective of modern finance theory.

So remember I was telling you the difference to Warren Buffett and modern finance. They do part company. Warren Buffett literally believes that he can pick stocks better than you and I can. And what academics would have you believe is that nobody can pick stocks, that it's all luck, and what you ought to do is simply buy the tangency portfolio. It's going to turn out that both of these perspectives are wrong, and they're right in very specific ways, and I'm going to show you how to put it together.

But let me first start by motivating this idea of efficient markets. Why you cannot make money, why all information is incorporated into market prices. And to do that, I'm going to tell you about a research paper that was published in 2003 by two economists, Michael Maloney and Herold Mulhearn, titled the complexity of price discovery in an efficient market, the stock market reaction to the Challenger crash.

Now this is a rather somber subject. It has to do with an event that occurred on January 28,

1986, at 11:39 AM. At that time, the Challenger space shuttle exploded before our very eyes. Apparently, one of the booster rockets ignited and destroyed the space shuttle.

11: 47, the space shuttle was reported to have exploded. It came across the news wire 12:17, Lockheed, which is one of the contractors that built the shuttle, had no comment. 12:52, Rockwell International, another one of the vendors that built parts for the space shuttle, they had no comment. This is all through the news wire.

And over the course of the next several months, a presidential commission was impaneled to study what happened with the space shuttle explosion. And many of you know, the physicist Richard Feynman was on that panel and wrote a dissenting opinion about what happened.

But the bottom line, after all the dust settled, was that in June of that year, so about six months later, there was a report that was produced that showed that it was an O-ring, a piece of rubber, around a booster rocket that ended up becoming brittle. And because it became brittle in the cold weather, there were gases that leaked from that booster rocket, and those gases ignited after take off. And so in the end, after all of this analysis, it was determined that the O-ring was at fault. And who produced this O-ring and the rocket? It was Morton Thiokol. They were the culprit, or the weak link in all of this, according to this study.

Now, this was on June 9, 1986. Let me show you what happened to the stock prices of all of the different vendors for space shuttle parts, right after the explosion on January the 28th, six months earlier. Let me show you a graph. There are four vendors. Lockheed, Martin Marietta, Rockwell, and Martin Thiokol. And these are the tick-by-tick price changes, all normalized to start at $1 at the very beginning of the sample, which was at 11 o'clock, or 11:39, when the shuttle exploded. So this is where we start, we all start with them at a dollar.

Within minutes of the explosion, I'm talking minutes now, not nine months or six months. Within minutes, we see that the stock price that gets hit the hardest is Morton Thiokol. All of them get hit. But by 1 o'clock, Morton Thiokol's price is down below all the others. And this is all normalized so that they all start off at 1. So it's not difference of scale, I've rescaled them. And moreover, at the close of trading on that day, the only stock that was down significantly, the only one, was Morton Thiokol. They had to stop trading in that stock because it was down so far.

This happened in less than six hours. It took the commission six months to come up with the

O-ring and Morton Thiokol. Now, if you look at this, you don't see an O-ring. But you see Morton Thiokol. Plain and simple, like a sore thumb. This is what I'm talking about. This is the wisdom of crowds. This is why, when you look at market prices, you should look at them with a certain degree of awe and respect. It's because it aggregates information like you wouldn't believe. It's phenomenal. So this is what economists like to trot out and say, see I told you so. This is what we're good at.

What I'm going to talk to you about on Wednesday is all of the other examples of where this fails. So this is the good news. On Wednesday, we're going to talk about the bad news.

OK, see you then.