What animal breeding can contribute

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Global trends
On the left we have a forecast for the number of people in the world, by income group. By 2050 there will be between 60 and 100 % more people in the low income group, and between 8 and 40 % more people in the medium income group. The high income group is not likely to change very much, that is the black line at the bottom: 1 billion people.

On the right we see that those low and medium incomes are going to be much higher than they are now, anywhere between 2 and 10 times as high.
Strong increase in number of people with low and medium incomes

Even stronger increase in their purchasing power
When people have more money to spend, they tend to consume more animal products, up to a plateau where about a third of the total calorie intake comes from fish and meat and eggs and milk. As always with this type of data there is a lot of variation, but the general pattern is very clear.
Strong increase in number of people with low and medium incomes

Even stronger increase in their purchasing power

Strong increase in the demand for animal food products
And there are modelling studies where this is actually quantified, for various parts of the world. The total length of each bar gives a prediction for 2050, this is per capita consumption of meat.
And when we multiply that per capita consumption with the expected number of people in those areas, we get the total meat consumption. As you see in the piecharts, we talk about a doubling in 40 years, and just about half of the worldwide meat consumption of 2050 will be in East and South Asia and the Pacific, the orange segment. The part of North America and Europe is still very significant but not at all as dramatic as it is today.
This is the (predicted) demand: what people **want**

Two very different things:

• **what people need**
  • healthy nutritional requirements

• **what the world can produce**
  • carrying capacity

**Political debate**

**Not about animal breeding**

That is the demand: what people **want**. Very different things are what people need for healthy nutrition, and what the planet can produce.

The scientists who study this kind of thing seem to be able to forecast just about every possible scenario, so this is largely a political debate. It is a very interesting debate, but we don’t have time for it here and now, the clock is ticking. And it also has very little to do with animal breeding.
Animal breeding
Animal breeding

• not: making more animals
  • (that is *multiplication*)

• but: making genetic changes
  • from one generation to the next
  • via selection of future parents
  • or via crossbreeding

  ➢ "genetic improvement"

• we don't cover
  • GMOs (that is not via selection)
  • cloning (that is for multiplication)
This comes from an FAO study, this part of it is about "policy objectives", that is what governments are supposed to worry about. In many cases this has implications for animal breeding goals.

We start here with a rural society, with low technical development and large numbers of small farmers. The main points of concern are usually food security (which means that everybody has enough to eat) and on the vertical axis here the livelihoods of all those farmers.
Then when industrialization starts, food safety becomes part of the picture. Remember: food security is that everyone has enough to eat, food safety is that all that food is actually safe to eat: not contaminated and so on. Which is not self-evident.
At a later stage politicians also start to worry about pollution. At that same time, society reaches the stage where food security becomes less of a continuous problem.
And here we have a fully urban society, post-industrial. Everybody has enough to eat, so food security is not on the political agenda anymore, and animal welfare has entered that agenda.

Of course at this stage, the livelihood of farmers is still important, but it is not something that governments worry much about. It is supposed to be taken care of by a fully developed market for agricultural products.
In the vertical dimension, there isn't really much that animal breeding (that is: genetic improvement) can contribute.

An important element is that "farmer livelihoods" have converted into "producer profitability", and those producers are customers of animal breeders.
In terms of food safety, animal breeding will have some role to play in the genetic improvement of traits like resistance against Salmonella and other bugs, and there is also the genetic management of local breeding populations.
But the main contribution by animal breeding is in the horizontal dimension here: a balance between on the one hand food security (that is the topic of this whole day, after all), and on the other hand environmental issues and animal welfare issues.
Animal breeding goals must find a balance between demands:
- for food security
- for
  - low environmental footprint
  - good animal welfare
- for producer livelihood
  (= customer profitability)

...i.e. the sustainability issue
Animal breeding goal traits

Demand for food security

• rate of production
  meat, eggs, milk per animal per day

• efficiency of production
  meat etc. per kg of feed
  progeny per female per year
  mortality and disease

economic efficiency
Animal breeding goal traits

Demand for low environmental footprint

• rate of excretion
  nitrogen, phosphorus, methane per animal per day

• efficiency of production
  nitrogen etc. excreted per kg of meat etc. produced

environmental efficiency
Animal breeding goal traits

Demand for good animal welfare

• **mortality and disease**
  robustness, resilience, resistance

• **pain**
  robustness, behaviour

• **frustration ← deprivation**
  behaviour
Examples
Animal breeding goal traits

Demand for food security

- **rate of production**
  meat, eggs, milk per animal per day

- **efficiency of production**
  meat etc. per kg of feed
  progeny per female per year
  mortality and disease
We have a 50-year trend here: the average milk production of Holstein cattle in the United States has doubled in that period, that is the dotted line. The solid line is the genetic trend, it shows that about 80% of the increase is due to genetic improvement.
USA: milk yield (1000 kg per lactation) in dairy cattle

Data from Animal Improvement Programs Laboratory, Beltsville, USA. aipl.arsusda.gov, Feb 2010
USA: milk yield (1000 kg per lactation) in dairy cattle

Data from Animal Improvement Programs Laboratory, Beltsville, USA. aipl.arsusda.gov, Feb 2010
A similar picture for laying hens in Germany, a 25-year trend. This is from random sample commercial product evaluations with a very constant environment, so a good indicator for genetic trends. Feed conversion has been improved from 2.9 to 2, and the total economic value has more than doubled from 7 to 16.
And a few 10-year genetic trend plots in pigs: lean tissue growth rate, feed conversion, and total mortality rate in 7 of my own lines. Very different profiles for the different lines, because they have different breeding goals focusing on different traits. That was not the case for the dairy cattle example and the laying hen example.
This is a different way of picturing a 50-year trend: there is an experimental broiler chicken line in north America that has been kept unselected since 1957, and this picture compares it with a commercial broiler chicken from 2007, both at 9 weeks of age.

The brown structures in front of the birds are cross-sections through the breast area, the fillets are at the bottom of each image.
That 1957 line was used in this famous experiment, where it was compared to a commercial broiler chicken of 2001, a Ross-308. And to make it really interesting, both genotypes were given feed from both periods. We see here on the right that the increase in breast muscle percentage is almost completely due to genetic differences, and on the left the majority of the increase in growth rate is also genetic. In the middle, the improvement of feed conversion is a fifty-fifty case of genetics and nutrition.
Animal breeding goal traits

Demand for food security

• rate of production
  meat, eggs, milk per animal per day

• efficiency of production
  meat etc. per kg of feed
  progeny per female per year
  mortality and disease
Animal breeding goal traits

Demand for low environmental footprint

• rate of excretion
  nitrogen, phosphorus, methane per animal per day

• efficiency of production
  nitrogen etc. excreted per kg of meat etc. produced
An example:
how genetic improvement reduces nitrogen excretion of growing pigs
This is data from 6 trials with growing pigs, they worked with 6 different breeds that were on the ground between 1969 and 2004. The measurements that were published can be converted into these two physiological traits: the black plot shows the maximum rate of body protein growth, which has almost doubled in those 35 years, and the white plot gives the amount of body lipid per kg of body protein, in the mature pig. This goes down from almost 5 to just above 1 kg lipid per kg protein in the body.

These two traits together form the basis of lean tissue growth rate, and of body lean content.
Of course, lean tissue growth rate can also be influenced by nutrition. These are 7 different diet recommendations from the NRC in the United States, they specify different protein and lysine content in the feed, for different target levels of lean tissue growth rate, or LTGR. All at the same level of feed energy content, and with a three-phase feeding strategy. And this assumes some kind of average pig from the genetic point of view.
I have combined those two things here: the 6 different pig breeds with their different genetic potential on the horizontal axis, and the 7 different feeding schemes. This gives a table with 42 cells, and this table can be filled in if we use the genetic information and the nutritional information as input parameters for a growth simulation model. Those models were developed for the prediction of protein intake and protein deposition, but they can also predict nitrogen excretion, because that is just the difference between the two.

So I have run that simulation model 42 times, and the results look like this.
We have the 7 diets and the 6 genotypes here, they make up the floor of the graph. On the vertical axis is the lifetime nitrogen excretion in kg, for a pig grown to 120 kg liveweight. The red line on the response surface shows for which diet each genotype has its lowest excretion. The green line shows for which diet each genotype has its highest nitrogen retention. Obviously these are different things.
And the red line shows that the minimum excretion of the 1969 breed was 5 kg per pig, and of the 2004 breed it was 4 kg. So a reduction by 20%.

These six breeds were all sirelines, they were mainly selected for high lean tissue growth rate, more or less the same thing as nitrogen retention.
how genetic improvement reduces nitrogen excretion

selection for lean tissue growth rate (= N retention) has reduced

• N excretion per 120-kg pig by 20 % in 35 years

when fed to minimum excretion

So, that type of selection, over 35 years, has reduced the lowest possible nitrogen excretion per slaughter pig by 20%.

Of course it has also increased the lean content of those pigs, that was the real purpose of the selection in the first place. So nitrogen retention has increased.
how genetic improvement reduces nitrogen excretion

selection for lean tissue growth rate (= N retention) has reduced

• N excretion per 120-kg pig by 20 % in 35 years

• N excretion per kg N retention by 25 % in 35 years

when fed to minimum excretion

So the environmental efficiency of the process, the amount of nitrogen excretion per kg of nitrogen retention, has increased more than 20 %: it has gone up by 25 %.

All that is for pigs that were fed to achieve their lowest possible excretion level, and nobody between 1969 and 2004 has ever done that. Pigs were supposed to be fed to achieve their highest possible retention, or something close to it.
So we need to look at the green line on the mesh plot, and there we see an excretion of 5.2 kg in the 1969 breed and 4.15 kg in 2004. That is a 25 % reduction.
how genetic improvement reduces nitrogen excretion

selection for lean tissue growth rate (= N retention) has reduced

• N excretion per 120-kg pig by 25 % in 35 years
• N excretion per kg N retention by 31 % in 35 years

when fed to maximum retention

So from that point of view, considering how pigs were actually fed, we get to improvement values of 25 % and 31%.
35 years of pig selection for N retention has reduced N excretion by 20 - 31 %

- side effect of selection for retention
- (correlated response)
- not intentional, not targeted
- we can do better, if targeted
- requires an active demand

So, dependent on how you look at it, we see an improvement in the environmental footprint by 20 to 30 %, and the important thing to remember is that this is a side effect of selection for something else – a correlated response as we say in animal breeding. Excretion was never targeted as a breeding goal trait in those years, which means that we should be able to do much better than 20 or 30 % if we do target that type of trait. It would not be difficult to get it organized in pig breeding, most of the elements are in place already. But breeders need an incentive to focus on new traits, and that requires an active demand for the product: someone must be willing to pay more for pigs that have a better environmental footprint. Once that happens, I'm sure that we can deliver the improved pig.
Animal breeding goal traits

Demand for low environmental footprint

- **rate of excretion**
  nitrogen, phosphorus, methane
  per animal per day

- **efficiency of production**
  nitrogen etc. excreted
  per kg of meat etc. produced
Animal breeding goal traits

Demand for good animal welfare

- mortality and disease
  robustness, resilience, resistance

- pain
  robustness, behaviour

- frustration ← deprivation
  behaviour
A good example that combines the issue of mortality and disease with the issue of pain is mastitis in dairy cattle. Mastitis is an infection of the mammary glands that is very painful for the cow. It is quantified routinely in terms of the count of white blood cells in the animal's milk, they call them "somatic cells" in the dairy industry. We see here that this cell count has been steadily going up in the USA dairy breeds since 1980. This was a side effect of the increase in milk production, combined with the inability to select against the somatic cell count, because there were no breeding value estimates available until 1998. In that year the breeding industry started to publish these breeding values, and then the somatic cell score trend comes to a stop first in Brown Swiss, a few years later in Holstein (and there it actually goes down very quickly), and the Jersey trend has also come to a halt by now.
An important welfare issue in poultry production is cannibalism, this is a laying hen example. The birds pull each other's feathers out, and that can easily escalate in going quite a bit deeper. That is obviously painful and dangerous for the bird at the receiving side, and poultry producers avoid it in practice by debeaking, which is what you see in the picture on the bottom: the tip of the beak is cut off at a very young age. And that creates a welfare issue at the actor side. So all parties involved would profit from a genetic solution, and the graph here shows that this is actually possible. This is a 5-generation selection experiment where they videotaped hens for 3 hours and then played the movie at high speed to count the number of feather pecks that each bird was dealing out, and they selected for a high or a low count. The difficult thing with this type of traits is that you need to find the actors, not the recipients – that would be a lot easier.

Something similar happens in pig production, with tail biting, ear biting, and vulva biting.
Animal breeding goal traits

Demand for good animal welfare

- mortality and disease
  robustness, resilience, resistance
- pain
  robustness, behaviour
- frustration ← deprivation
  behaviour

Coming back to our animal welfare overview...
Animal breeding goal traits

Demand for good animal welfare

- mortality and disease robustness, resilience, resistance
- pain robustness, behaviour
- frustration \leftarrow deprivation behaviour

better adaptation to intensive conditions

PW Knap (2011) Pig breeding for increased sustainability. Encyclopedia of sustainability science and technology, Springer, Germany

…the third element is about breeding of animals that are better adapted to intensive production systems because their instinctive behaviour patterns have been changed. I think we will see a strong increase of intensive production systems, particularly in Asia and Latin America, so the topic is going to be very relevant in the sustainability discussion. But I’m going to skip it here because it is a very large topic and we don’t have time for it.

But on the bottom there is a reference to some text that I wrote about it, so you can look it up if you’re interested.
End of examples
Animal breeding goals must find a balance between demands:

- for food security
- for
  - low environmental footprint
  - good animal welfare
- for producer livelihood
  (= customer profitability)

...i.e. the sustainability issue
Animal breeding goals must find a balance between demands. 
This is feasible (see examples)
Possible bottlenecks for successful implementation:
1. Antagonisms between traits
2. Genotype x Environment interaction
3. Inadequate selection tools
4. Inadequate selection and mating

Animal breeding goals will have to find a balance between the various demands, and I hope that my examples have shown that this is actually feasible.
There are at least four reasons why things can go wrong in animal breeding: antagonistic relations between traits, genotype by environment interaction, inadequate technology, and inadequate selection and mating strategies. We are going to have a look at the first three.
Antagonisms
Antagonistic traits

• improvement of one trait leads to reduction of another trait
  often fitness traits: robustness, fertility

• can be neutralized
  balanced breeding goals

We are talking about correlated responses again, just as with the nitrogen excretion example of a few minutes ago, but this time the correlated response is unfavourable. The most common problem is that improvement of a production trait leads to trouble with fitness traits, usually robustness or fertility. This can be neutralized by designing the breeding goal in a proper way.
Here are the genetic trends of the production trait again…
…and we have already seen the correlated responses in the fitness trait mastitis incidence...
...and here we have the same for a fertility trait: pregnancy rate. The downward genetic trend comes to a halt just after the year 2000, again because of more focus on this fitness trait in the breeding goals of these breeds...
…which is what we see in this graph: the focus on production traits (the white part) and the focus on fitness and conformation traits in the Holstein breeding goal in the United States. From 1996 to 2009, the fitness and conformation traits get steadily more focus.
Now we squeeze the graph a bit to make more space…

Data from S Schneider (2009) 2009 World index. Holstein International 16(6):26-31
Holstein dairy cattle breeding goals: 1994 to 2009

...so that we can add the corresponding graph for Holland, where we see the same pattern, but a bit more extreme...
…and very similar patterns in several other countries. The graph on the far right is the world average. The focus on production traits has come down from 80% in 1994 to 50% in 2009, and I think there will be more change to come.
Our pig example from some minutes ago shows the same principle: you notice that all these lines show improvement in production traits on the top left, and in feed efficiency on the top right, and in fitness traits on the bottom, all at the same time. That is because those traits are all part of the breeding goals.
Another example in pigs: most pig breeding companies have made considerable progress in litter size, particularly after BLUP was generally implemented.
But there is an unfavourable correlation between litter size and piglet survival rates, we see that here in one of my own sow lines. In the year 2000 the relation between the two traits was negative, and in 2008 that was still the case. But in those 9 years the plot has moved to the right, which means that litter size has increased, and it has also moved up, which means that piglet survival rate has improved at the same time…
…and we see the same in the years in between, and also in another of our sow lines, on the right. We have here an unfavourable genetic correlation that is neutralized through breeding. Genetic antagonisms can be broken, simply by giving enough focus in the breeding goal to all relevant traits.
And this is what comes out of that, in our sow lines. On the bottom, litter size goes up, and in the other two graphs, survival rates are going up at the same time.
Animal breeding goal traits

Antagonistic traits

• improvement of one trait leads to reduction of another trait
  often fitness traits: robustness, fertility

• can be neutralized
  balanced breeding goals
The next topic is genotype by environment interaction...
Animal breeding goal traits

Genotype x Environment interaction

• improvement in environment A does not fully work through in environment B due to different climate, health, nutrition, management, …

…which happens when the genetic improvement that is achieved in a particular environment does not get carried over completely to other environments. That may be due to differences in climatic conditions, in animal health, nutrition, animal management, or simply because…
... animals are used for additional functions in different production systems. For example, we should not expect dairy cows with very high genetic merit for milk production, to perform up to spec in a production system like this here.
An example, based on the USA dairy genetic trends again…
...if we take out the Brown Swiss ...
USA: milk yield (1000 kg per lactation) in dairy cattle

...and stretch the whole picture a bit to make space at the bottom...
…then we can add the corresponding trends for those two cattle breeds in Costa Rica. We see phenotypic improvement (the dotted lines) at about the same speed as in the United States, but the genetic trends are almost horizontal. The authors of this article blame that to two factors: in the first place the widespread use of bulls of low genetic merit from the local sector (so the point of inadequate selection and mating of a few minutes ago), and in the second place: genotype by environment interaction between Costa Rica and the United States…
...because they have used lots of American AI bulls. Here we see how those bulls rank when evaluated on daughter performance in USA (on the horizontal axis) and in Costa Rica (on the vertical axis). The two axes in this graph are to scale, so there really is 70% more spread in the estimated breeding values based on USA records. And that means 70% more potential genetic improvement from selecting the top bulls.
I have a nice example of exactly the same thing in pigs, this is for litter size. We have here 300 thousand records of daughters of about 2000 of our AI boars, these sows have lived on 144 farms in very different parts of the world as you can see on the little map on the right.

The environmental level of the farm by season effect is on the horizontal axis here, from left to right the environmental conditions are improving. As you would expect, the overall trendline through all these data goes up: better conditions lead to better performance.
And because we know who the fathers of those sows were, we can do that analysis for each daughter group separately, here we have the two extreme ones: the AI boar on the bottom produces daughters with a low litter size, and this genetic potential is not sensitive to the environment: when the conditions improve, performance just remains poor.

The blue AI boar on the top produces daughters with a very high potential, but this potential is very sensitive: if you don't manage them properly, they don't express all of their genetic merit.
And all the other daughter groups are somewhere in between. The pattern is very stable: the higher we get in the graph, the steeper becomes the slope of the trendlines, so we get more environmental sensitivity. This way, we can unravel the genotype by environment interaction down to the level of the individual animal. This shows the same thing as the Costa Rica cattle plot of a minute ago: the spread of the estimated breeding values is much lower in the poor environments on the left. So there is less scope for genetic improvement there.
A very specific example of environmental sensitivity comes from the Dutch pig breeding company Topigs. Here we have one of their sow lines, that was selected for litter size based on data recorded in Holland. Reproductive performance is nicely high up to an ambient temperature of 23 centigrades, but above that it falls apart very quickly.
after 15 years of selection on records from…
Holland
Holland, Spain, Italy, Brazil & Philippines

litter size in 2 Topigs pig lines: climatic sensitivity

piglets born per first insemination

temperature at insemination (C)

The black plot is for another sow line, also selected in Holland for litter size, but on breeding value estimates that were based on data recorded not only in Holland but also in a few much warmer countries.

This line does not show the big crash of reproductive performance at higher temperatures, and above 26 centigrades it performs considerably better than the white line. A complete change of rank due to climatic sensitivity of the genetic potential.
Animal breeding goal traits

Genotype x Environment interaction

• improvement in environment A does not fully work through in environment B due to different climate, health, nutrition, management … can be neutralized
• select breeding stock in A on data recorded in B (= in the target environment)

Just as with the antagonisms between traits, genotype by environment interaction can be neutralized by appropriate breeding strategies. One of the options is to select breeding stock at the nucleus level, on breeding value estimates that are based on data recorded in the target environment, like in the black line of the previous slide where many of the records came from hot climates.
Here the new nucleus generation is selected based on data recorded in that same nucleus environment. This is the default.
And here we use data from the commercial level in B to support that selection in the nucleus, in A. This requires a faster genetic connection between the top and the bottom of the pyramid, that is the dotted red arrow. Otherwise the data from B come too late to be really useful for breeding value estimation in A.
AI bull's breeding value estimated from data recorded in USA

AI bull's breeding value estimated from data recorded in Costa Rica

17 best Holstein bulls, on USA records (A) versus Costa Rica records (B)

Back to our Costa Rica example: I have indicated the best 17 Holstein bulls here. In blue based on their estimated breeding value from USA daughters, and in red based on their Costa Rican daughters. There is only one bull that appears in both groups, that is the purple datapoint at the top right. The blue bulls have a genetic merit for the Costa Rican environment of +248 kg milk, the red bulls average at +511 kg...
...which means that if Costa Rican producers would select USA bulls based on Costa Rican performance data, they would double the effective selection intensity, and therefore double genetic improvement.

The simple fact that this particular graph exists, means that those data are actually available in Costa Rica, and that there is also someone there who knows how to convert them into estimated breeding values. The rest is just a matter of getting things organized.
The alternative is of course to forget about environment A in the first place, and to set up a nucleus breeding structure in the target environment itself. Here we have a webpage of a pig breeding company in Australia. These people used to run a nucleus system in the tropical north of Australia, to develop lines designed specifically for the hotter climates, as they state in the red box on the top.
And a similar example for poultry breeding in India, targeting harsh low-input conditions, as you can read in the two blue boxes on the left.
milk yield (1000 kg per lactation) in dairy cattle

Back to the USA and Costa Rica trends again…
Data from Animal Improvement Programs Laboratory, Beltsville, USA. aipl.arsusda.gov, Feb 2010

Data from B Vargas & G Gamboa (2008) Genetic trends, genotype-environment interaction... Téc Pecu Méx 46:371-386

Data from AE Vercesi et al (2010) Selection of tropical dairy cattle... 9th WCGALP conference, Germany, comm 0829

Data from Animal Improvement Programs Laboratory, Beltsville, USA. aipl.arsusda.gov, Feb 2010

...we can add trends from just such a local breeding program in Brazil, for the Gir Leiteiro breed. We see here a much stronger genetic trend than for the Costa Rican Holstein and Jersey populations...
…which may be the reason why semen of the Gir Leiteiro and other Zebu varieties is exported from Brazil all over the tropical world, these days.
select breeding stock in A on data recorded in B

But let's come back to the previous strategy…
…which has been routine in poultry breeding for a few decades now, they call it recurrent selection, so they produce recurrent test information from environment B.
At PIC we have implemented this in our pig breeding program about ten years ago. This example is to show that if you organize it properly, then the genetic improvement of traits like growth rate and litter size can be just as fast at the commercial level in Chile (the broken lines) as at the genetic nucleus level in Canada (the solid lines).
<table>
<thead>
<tr>
<th>Animal breeding goal traits</th>
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<tr>
<td><strong>Genotype x Environment interaction</strong></td>
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<tr>
<td>• improvement in environment A does not fully work through in environment B due to different climate, health, nutrition, management, …</td>
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<td><strong>can be neutralized</strong></td>
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<tr>
<td>• select breeding stock in A based on data recorded in B</td>
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<td>• set up local breeding programs</td>
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So, we have these two strategies to neutralize genotype by environment interaction…
Animal breeding goal traits

Genotype x Environment Interaction

- Improvement in environment A does not fully work through in environment B due to different climate, health, nutrition, management, etc.
- Can be neutralized
- Select breeding stock in A based on data recorded in B
- Set up local breeding programs
- Improve the conditions in B

...but the most effective one is of course to improve the conditions in the commercial environment. Our sow daughter groups show that this has two advantages. In the first place, average production will go up, that is nothing new, and we will need it very much if we have to produce twice as much meat in 2050. In the second place, the variation between genotypes becomes much wider when we move to the right in the graph, which means that the better animals become more better: it is much easier to actually profit from superior genetics. That will be very helpful too.
Now, I have been using the term "estimated breeding value" all the time, we need to have a quick look at the technology behind these things.
The classical way that animal breeding used to be performed is by selecting the parents of the next generation based on their own performance, for whichever trait is of importance at the time. That is very easy to do, and it works fine for traits with high heritabilities.

Around 1990 this was much improved by the introduction of BLUP, which is just a statistical method to take data from relatives into account. Because of that, it requires a pedigree, and it really works best with lots of data. So you need a computer for it. The power is most clear for traits with low heritabilities…
…such as litter size in pigs. As I said some time ago, the genetic trends for this trait only started to lift off a few years after each of these 10 breeding companies implemented BLUP, that was in different years for different companies, the orange one here was the latest to get it sorted out. But once you use BLUP, you get genetic improvement. This was a true revolution.
Animal breeding tools

1. Selection on own performance
   - easy, uncomplicated
   - only for traits with high $h^2$

2. Selection on BLUP
   - requires pedigree
   - requires many records
   - requires computer
   - also for traits with low $h^2$
   - also for records from environment B

BLUP is also the most convenient way for doing something useful with data that were recorded in the commercial environment.
And then we need to cover genomic selection, a very hot topic in animal breeding these days, the new revolution. Basically, an extended version of marker-assisted selection. It requires everything that you also need for BLUP, although the need for pedigrees is not so strong in some cases. And it requires genotyping for large numbers of DNA markers. This makes it an expensive method, although the prices of genotyping have been coming down very dramatically the past few years, while the technology is maturing.

This methodology works fine for traits that are hard to measure, for example because they require expensive equipment or complicated designs, like disease resistance, or because you have to wait for them for a long time, like with cow or sow longevity.
This is from the USA dairy website again, these graphs are called "Manhattan Plots" because of the skyscraper architecture. We are looking at the 30 cattle chromosomes in different colours from left to right, with the effects of about 50 thousand DNA markers scattered across those chromosomes. Effects on traits such as milk production, on the top, and then milk protein, and the mastitis trait: somatic cell score. The vertical scale is in genetic standard deviation units of the trait, and we see that each marker on its own explains less than 1 % of a genetic standard deviation, with a few exceptions that make it to 4 % or so, like for milk production on chromosome 6.

But there are 50 thousand of them, and that adds up.
Another trait: the effect of the father of a calf on possible problems during birth of that calf. There is a major gene on chromosome 18…
…and that same gene has a clear effect on the counterpart trait, the effect of the mother of the calf. And there is something similar on chromosome 12.
And just a final example of another major gene, this time on chromosome 14, and it influences milk fat production.
All those traits in the breeding goal can be analyzed this way, here we have the total economic value of all USA Holstein breeding goal traits together. On average, each marker covers between 1 and 2% of a genetic standard deviation.
And the same patterns for the other two dairy breeds. These are the same DNA markers, for the same traits, but we see that they are less powerful in Jersey than in Holstein, and even less so in Brown Swiss. This is due to the population structures of the breeds: the Holstein population has a relatively small number of relatively large families, and that helps for more powerful DNA marker processing.
So, back to Holstein…
…when a young bull is around puberty, his breeding value can be estimated, by BLUP, with a reliability of about 30%. At that point in time the available data is mostly on animals from earlier generations, like his mother and his father. A young bull is selected on that estimated breeding value, and put on progeny testing, and 4 or 5 years later his daughters have produced records that increase the reliability of his breeding value estimate to 80%. This is what dairy cattle breeding was all about, up to now. It is a slow and very expensive process.
The genomic information from all those markers leads to a reliability that is just a bit lower than for the progeny test, **but** it can be made available at a very young age, basically from the moment we can sample some DNA from the animal…

genomic prediction in dairy cattle: improvement of breeding value estimation

reliability of bull's breeding value estimate (%)

• Select bulls around puberty with 90% of the reliability of a progeny test
• Stop progeny testing
  • reduce cost
  • reduce generation interval
• Make genetic improvement faster and cheaper

Data from Animal Improvement Programs Laboratory, Beltsville, USA. aipl.arsusda.gov, Feb 2010

…and that leads to a scenario where bulls can be selected at a young age with a reliability that comes very close to progeny testing. And because progeny testing is expensive and slow, it is feasible to just abandon it and shift to genomic selection instead. That makes genetic improvement faster, because of the much shorter generation interval, and it makes it a lot cheaper at the same time.
That holds for the Holstein breed, and what I just described is actually happening all over the Holstein world right now. The other two breeds have much lower Manhattan plots, and this shows in the reliability of their genomic breeding value estimates. So, here the move away from progeny testing is much less obvious, it will require some serious cost-benefit analyses.
And this is just to show that the same pattern holds for all the individual traits that make up the total economic value.
A quick example for the same issue in pigs, this is for litter size in one of our sow lines. On the left we see how the BLUP breeding value estimate of a young boar correlates to his true breeding value (which we will find out only after a long time, when his daughters have started to produce litters).

On the right is the same correlation plot for the genomic estimated breeding value. The difference may not look very dramatic, but it is a 50 % increase in reliability, so a 50 % increase in genetic improvement if you select on those numbers.
Animal breeding tools 2

Genomic selection

- requires pedigree (?), many records, computer
- requires genotyping
- also for hard-to-measure traits
- ideal for records from environment B

- very young technology
  - first serious applications in 2009
- very much under development

So, this is a very young and immature technology, fully under construction…
Animal breeding tools 2

Genomic selection
• requires pedigree (?), many records, computer
• requires genotyping
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• ideal for records from environment B

• very young technology
  • first serious applications in 2009
• very much under development

… we are just dealing with the tip of the iceberg right now.
Which means we should go under water and have a look at the rest of the iceberg. Peter Best our moderator asked me to speculate a bit about future possibilities.
Livestock has changed considerably, and there are all those genetic trends pointing upwards. The question is: where is it going to stop?

First I am going to show you three examples of long-term selection for a particular trait.
Here we see that body weight has been doubled from 30 to 60 grams after 72 generations of selection, and the trend goes on without any sign of slowing down…
...just as it does here. Body weight has tripled from 90 to 270 grams in 86 generations, and no sign of slow-down further on.
A more commercially interesting species, the famous Illinois corn experiment. Oil content of the yellow line has quadrupled from 5 % to 20 % after 85 generations, and at that same time all the oil had disappeared from the seeds of the orange line, so they couldn't take it down any further.
We have seen this picture before, the 2007 genotype weighs more than four times as much as the 1957 genotype.
This is an impressive difference…
…but it is almost negligible compared to the various horse and dog genotypes. These are four healthy adult individuals, showing very effectively what animal breeding can achieve.
Now a bit of forecasting.
The yellow trendline here represents the population average of this pig breed. Every black dot represents the genetic merit of an individual pig. What we see is that animals that were just about average in 2010 were pure science fiction, nine generations earlier. Such animals did simply not exist, at that time.
Back to Holstein. The Manhattan plot shows the effects of 50 thousand DNA markers, in terms of how they influence the trait that we are talking about.

Any animal in the population carries two copies of each marker (one from its father, one from its mother) and each of these can have a positive effect on the trait, or a negative one, of the magnitude indicated in the Manhattan plot. On average, they cancel each other out: the average breeding value in the population is always zero.

The plot on the bottom shows how this happens to be arranged on the chromosomes of the AI bull in the picture, name of Freddy, who was the Holstein individual with the highest genetic merit in the world: 911 US dollars above the population mean, in August 2009. I looked him up on the Web, Freddy is still ranking very high.

We see that this is mainly due to Freddy's genes on his chromosomes 1, 2, 10, 11, 19, etcetera. Freddy is just about average for the genes on chromosomes 3, 15 and 26, and he could have done much better on chromosomes 5, 9, 12 and 14.
Here we have 30 similar plots for 30 other Holstein animals, each of them is world champion for total economic value on one particular chromosome, the red one in each plot.

So the individual chromosomes with the best configuration of 2009 were in fact located in 30 different cows or bulls. Which makes you wonder what would happen if we could bring them all together in the same individual.
And that is what we have here: a hypothetical cow with an estimated breeding value of 3148 US dollars above the population mean of August 2009. That is 3.5 times the value of Freddy, the real-life Holstein world champion of 2009.

This cow did not exist at that time, and the authors calculate that it will take 77 years for classical BLUP selection to arrive there. But at the end it will, that is what genetic improvement is all about.
There are clever ways to introduce single chromosomes (like number 5, or number 23) from a donor population into a recipient population. This involves several generations of crossbreeding, guiding the process by selecting the parents of the next crossbred generation based on DNA markers that are located on that particular chromosome.

Nothing to do with GMOs, just educated crossbreeding.
And here we look at the chromosomes of the rat, where genes have been found that influence blood pressure. Obviously, this is a model system for human medicine studies. Notice that such genes have not yet been found on chromosomes 6, 11 and 15.
This is from an experiment where this marker-assisted crossbreeding technique was used to substitute each of the chromosomes of a normal rat line, one by one, into a rat line that is genetically equipped with high blood pressure.
The normal line, in white, has a blood pressure of 110 units just like you and me. The other line, in blue, is at 175 units…
…and this is what happens when chromosome 5 of the normal line is substituted into the high-blood-pressure line: blood pressure goes down from 175 to 130 units, and that must be due to the genes that were found there, they are pretty powerful ones.
Many of the other chromosomes have a similar effect. The green datapoints are for chromosomes where high-blood-pressure genes had been found and that do show an effect, or for chromosome 6 (just left of the blue bar) where such genes had not been found and its shows no effect.

The red datapoints show false negatives or false positives. Obviously, the thing is not perfect yet, for several reasons…
…but it does illustrate the point that I am trying to make here. The high-blood-pressure line is 48 units higher than the normal line, but when we accumulate the effects of the genes on its individual chromosomes, we come to 341 units. Now, nobody would ever want to reduce the blood pressure of a rat by 341 units, that would be very bad for the animal, but it illustrates that there is more than 700 % scope for optimization by careful manipulation of the system.
So, here she is again. Fasten your seat belts, it’s getting really bumpy now.
I am combining the results from Freddy the Holstein bull with the results from the rats with high blood pressure. They have nothing to do with each other, but we all know how NASA got people on the moon. The outcome is 25 magnitudes of scope for genetic improvement, assuming very careful use of the correct technology.

This is not the type of animal breeding that you do on a Saturday afternoon in the backyard, with help from uncle George who has been judging breeding stock all his life.

Even more important: it does not involve GMOs. No individual animal has to be manipulated for this to happen. It is just crossbreeding and selection.
An important element here is that genetic variation does not disappear very fast, with selection. The red curly brackets on the far left and on the far right show that the spread of breeding values stays about the same, although the population mean changes very considerably.
Will it / can it go on like this? Where is the limit?

• From this example:
  • genetically, to a population mean at \(25 \times\) the current extreme value
  • Genetic variation does not disappear

So, there are two take-home messages here: the limit to genetic improvement is very far away indeed, and much of this is due to the fact that genetic variation in livestock populations does not easily disappear.
Nobody believes this, of course
Nobody believes this, of course

I hardly believe it myself

I hardly believe it myself. But we have just calculated it…
Nobody believes this, of course

> 25

…and we must remember that the body weight difference between these two adult members of the same species is considerably more than a factor of 25…
Nobody believes this, of course

"The world market has space for about five computers, not more [...] only the largest governments and corporations will ever need or want computers"

*Thomas J. Watson, CEO of IBM (1943)*

…and if there is anything that we cannot believe, we must always remember the famous words of the guy who invented the commercial computer, some decades ago.

Forecasting is a very tricky business. My crystal ball is just as good as his, but perhaps I am less pessimistic.
Will it / can it go on like this? Where is the limit?

- From this example:
  - genetically, to a population mean at 25 × the current extreme
  - Genetic variation does not disappear

- Genetic constraints
  - interactions between genes
    - requires very careful methods

- Biological constraints

As always, there are constraints. Genetic ones, like we saw with the 341 blood pressure units of the rat: the genes interact with each other, and it is going to be challenging to get everything under control.

And more close to home, biological constraints…
Will it / can it go on like this? Where is the limit?

- Biological constraints
  - lower limits (= 0) to incidence values (mortality, disease, ...)
  - lower limits (< 100 %) to efficiency

...because obviously some traits will hit a lower limit, like with the oil content of the corn.
And surely with efficiency...
...we have seen this already, the feed efficiency trends are at the top here...
...and one of the poultry breeding companies is forecasting a plateau in that trait, the coming decade.
Will it / can it go on like this? Where is the limit?

- **Biological constraints**
  - lower limits (= 0) to incidence values (mortality, disease, ...)
  - lower limits (< 100 %) to efficiency
  - lower limits to % of vital body parts (organs, skeleton, fat)
  - lower limits to maintenance requirements → sensitivity

There are also lower limits to any of the vital processes in the body, most notably the maintenance requirements.
So the really important thing for the next few decades will be to keep a healthy balance between short-term and long-term interests, between production and robustness. The body support functions will have to be respected and supported.
Will it / can it go on like this? Where is the limit?

- Biological constraints
- Requires balanced breeding goals
- Requires improved conditions for improved genotypes

But perhaps the most important issue is that the world will need better production conditions for the improved livestock genotypes that are in the pipeline everywhere. Without that, it is not going to work. Animal production will have to get professional, pretty soon. Sustainable farming is going to be equal to precision farming, especially towards 2050.
What animal breeding can contribute:

Summary
I think we can safely conclude that animal breeding and its technology will be able to support a doubling of the production of meat and eggs and milk the coming 40 years. The potential scope for improvement is very large...
What animal breeding can contribute

• **Scope for further improvement is very large**

• **Limiting factors:**
  - nutrition, health care, management
  - careful use of the right technology: balanced breeding goals

…and the possible limiting factors are not difficult to identify. But they will have to be resolved.

And the breeding technology as such, will require a lot of attention. Sustainable animal breeding is going to equal high-tech animal breeding, particularly towards 2050.
What animal breeding can contribute

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