Scientific foundations of the **DeFuse** project – demining by fusion of techniques

DeFuse

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DTU

Scientific objectives

- Obtain general scientific knowledge about the advantages of deploying a combined approach
- Eliminate confounding factors through careful experimental design and specific scientific hypotheses
- Test the general scientific hypothesis is that there is little dependence between missed detections in successive runs of the same or different methods
- To accept the hypothesis under varying detection/clearance probability levels
- To lay the foundation for new practices for mine action, but it is not within scope of the pilot project

Are today's methods not good enough?

- some operators believe that we already have sufficient clearance efficiency
- no single method achieve more than 90% efficiency
- clearance efficiency is perceived to be higher since many mine suspected areas actually have very few mines or a very uneven mine density
- today's post clearance control requires an unrealistically high number of sample to get statistically reliable results

Are combined methods not already the common practice?

- today’s combined schemes are ad hoc practices with limited scientific support and qualification
- we believe that the full advantage of combined methods and procedures has not yet been exploited

Does the project require a lot of new R&D?

- no detection system R&D is required
- start from today's best practice and increase knowledge about the optimal use of the existing "toolbox"

Is it realistic to design optimal strategies under highly variable operational conditions?

- it is already very hard to adapt existing methods to work with constantly high and proven efficiency under variable operational conditions
- proposed combined framework sets lower demand on clearance efficiency of the individual method and hence less sensitivity to environmental changes
- the uncertainty about clearance efficiency will be much less important when combining methods
- overall system will have an improved robustness to changing operational conditions

Outline

- **DeFuse** objectives
- Statistical modeling
- The design and evaluation of mine equipment
- Improving performance by statistical learning and information fusion

Scientific approach

Scientist are born sceptical: they don’t believe facts unless they see them often enough

Why do we need statistical models?

- Mine action is influenced by many uncertain factors – statistical modeling is the principled framework to handle uncertainty
- The use of statistical modeling enables consistent and robust decisions with associated risk estimates from acquired empirical data and prior knowledge
- Pitfalls and misuse of statistical methods sometimes wrongly leads to the conclusion that they are of little practical use

The elements of statistical decision theory

Data

- Sensor
- Calibration
- Post clearance
- External factors

Prior knowledge

- Physical knowledge
- Experience
- Environment

Statistical models

ss function

- Decision
- Risk assessment

Inference:

Assign probabilties to hypotheses

What are the requirements for mine action risk

- Tolerable risk for individuals comparable to other natural risks
-
- d

  commercial etc.)

Goal

•99.6% is not an unrealistic requirement

•But… today’s methods achieve at most 90% and are hard to evaluate!!!

GICHD and FFI are currently working on such methods [Håvard Bach, Ove Dullum NDRF SC2006]

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Evaluation and testing

- How do we assess the performance/detection probability?
- What is the confidence?

Detecting a mine – flipping a coin

$$Frequency = \frac{\text{no of heads}}{\text{no of tosses}}$$

$$probability = frequency \text{ when infinitely many tosses}$$

99,6% detection probability

$$Frequency = \frac{996}{1000} = 99{,}6\%$$

$$Frequency = \frac{9960}{10000} = 99{,}60\%$$

One more or less detection changes the frequency a lot!

Inferring the detection probability

- N independent mine areas for evaluation
- y detections observed
- true detection probability θ

$$P(y \mid \theta) \sim \text{Binom}(\theta \mid N) = \binom{N}{y} \theta^{y} \theta^{N-y}$$

Incorporating prior knowledge via Bayes formula

$$P(\theta \mid y) = \frac{)\,p(\theta)}{P(y)}$$

prior

Prior probability of θ

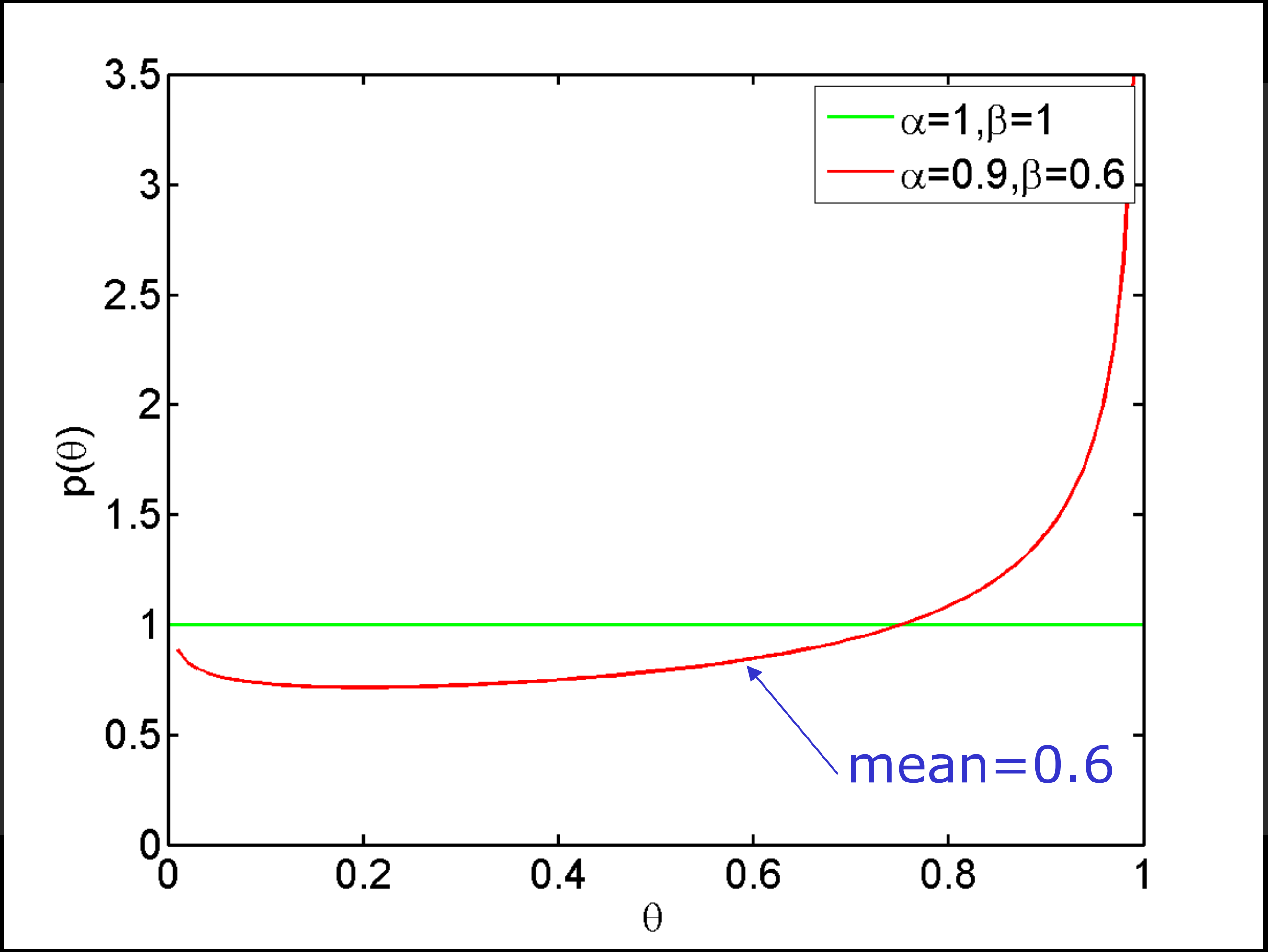
- No prior
- Non-informative prior

$$p(\theta) = Uniform(\theta \mid 0,1)$$

- Informative prior

$$p(\theta) = Beta(\theta \mid \alpha, \beta)$$

Prior distribution

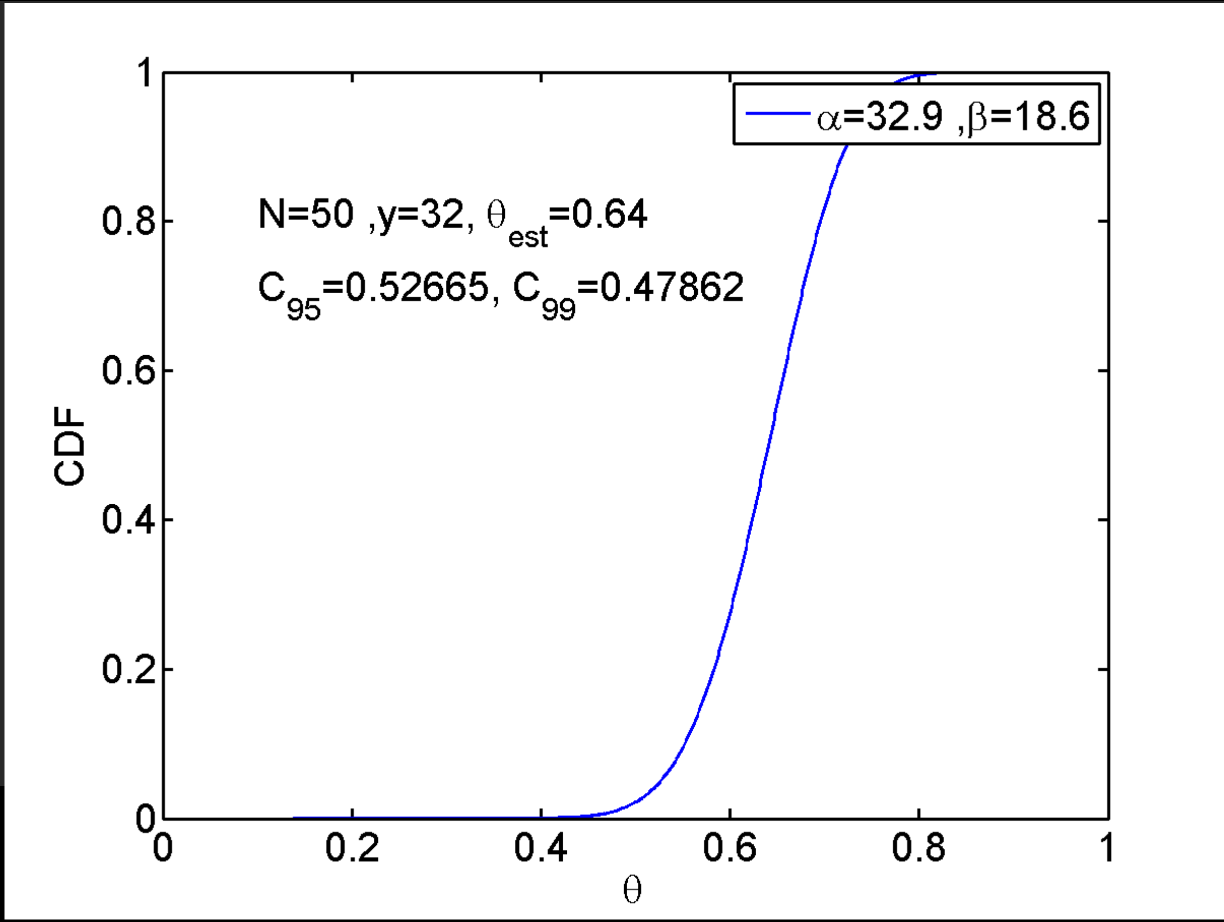


Posterior probability is also Beta

$$P(\theta \mid y) = Beta(\theta \mid y + \alpha, \beta + n - y) \sim \theta^{y+\alpha}\theta^{n-y+\beta}$$

HPD credible sets – the Bayesian confidence interval

$$C_{1-\varepsilon} = \{\theta: P(\theta \mid y) \geq k(\varepsilon)\},\ P(C \mid y) > 1 - \varepsilon$$



The required number of samples *N*

- We need to be confident about the estimated detection probability

$$\text{Prob}(\theta > 99.6\%) = C_{1-\varepsilon}$$

	$C_{95\%}$	$C_{99\%}$
$\theta_{est} = 99.7\%$	9303	18994
$\theta_{est} = 99.8\%$	2285	3995

Uniform prior

	$C_{95\%}$	$C_{99\%}$
$\theta_{est} = 99.7\%$	8317	18301
$\theta_{est} = 99.8\%$	2147	3493

Informative prior

α=0.9, β=0.6

The required number of samples *N*

- We need to be confident about the estimated detection probability

$$\text{Prob}(\theta > 70\%) = C_{1-\varepsilon}$$

	$C_{95\%}$	$C_{99\%}$
$\theta_{est} = 85\%$	13	39
$\theta_{est} = 80\%$	44	99

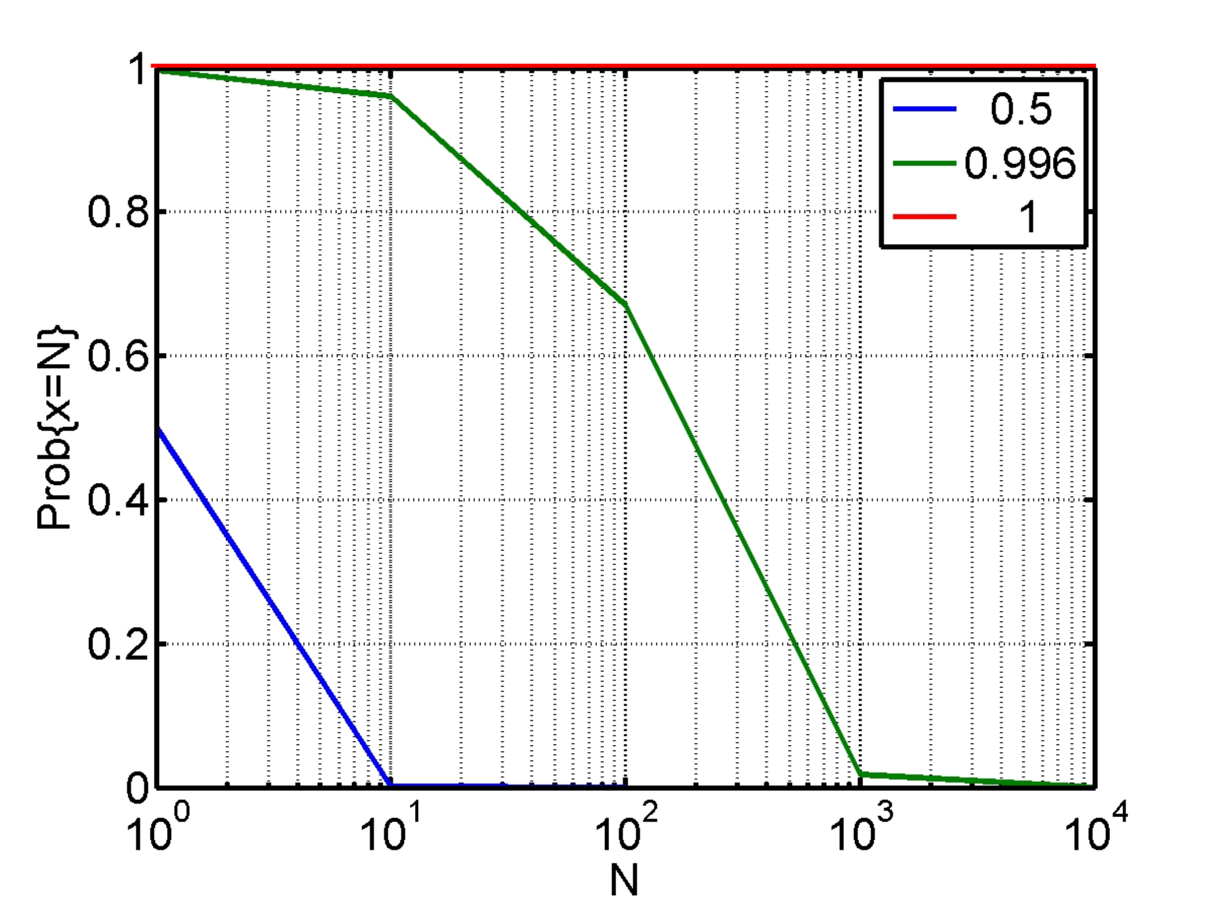
Uniform prior

	$C_{95\%}$	$C_{99\%}$
$\theta_{est} = 85\%$	12	33
$\theta_{est} = 80\%$	39	89

Informative prior

α=0.9, β=0.6

Probability of seeing a sequence of only true detections



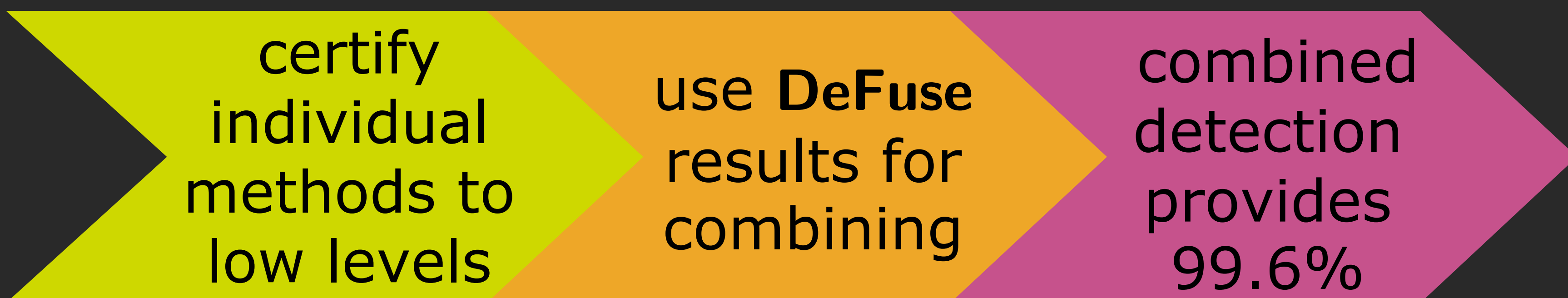
Credible sets when detecting 100%

Minimum number of samples N

	Prob($\theta > 80\%$)	Prob($\theta > 99.6\%$)	Prob($\theta > 99.9\%$)
$C_{95\%}$	13	747	2994
$C_{99\%}$	20	1148	4602

Consequences

- It is unrealistic to check 99.6% detection rate is post clearance tests
- It is realistic to certify individual method to e.g. 70% detection rate



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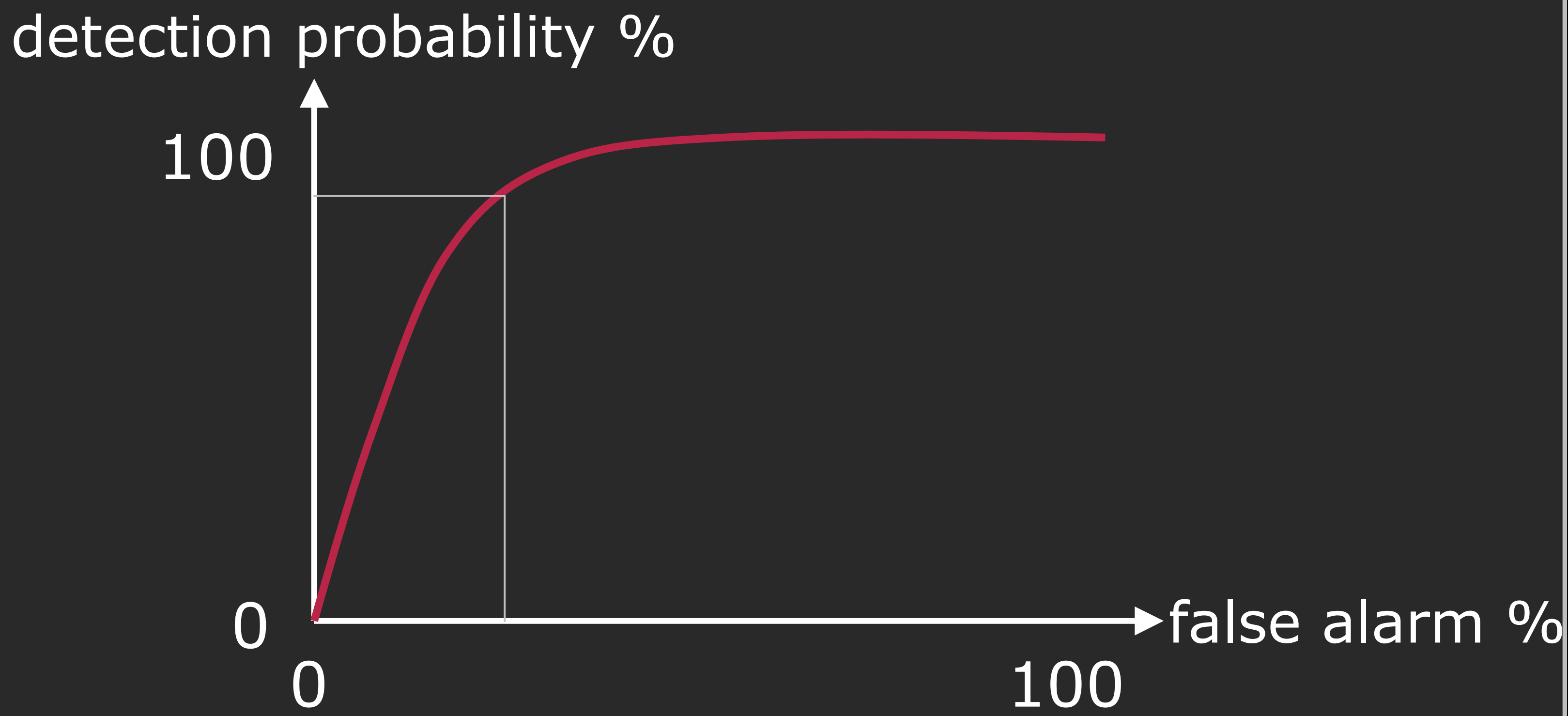
Confusion matrix captures inherent trade-off

		True	
		yes	no
Estimated	yes	a	b
	no	c	d

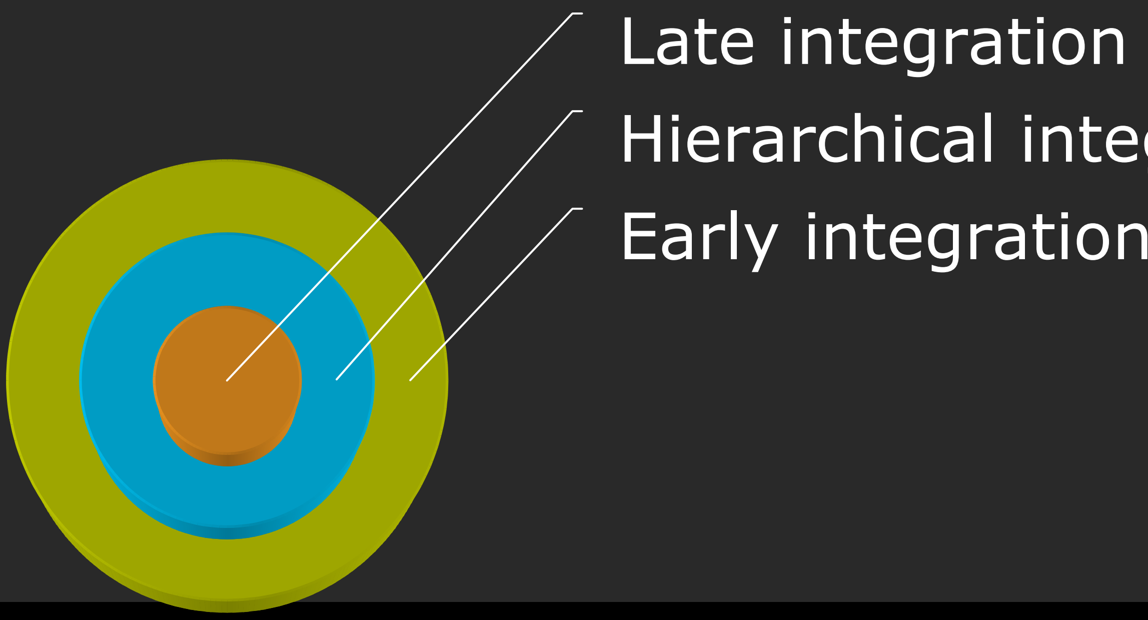
- Detection probability (sensitivity): a/(a+c)
- False alarm: b/(a+b)

Receiver operations curve (ROC)

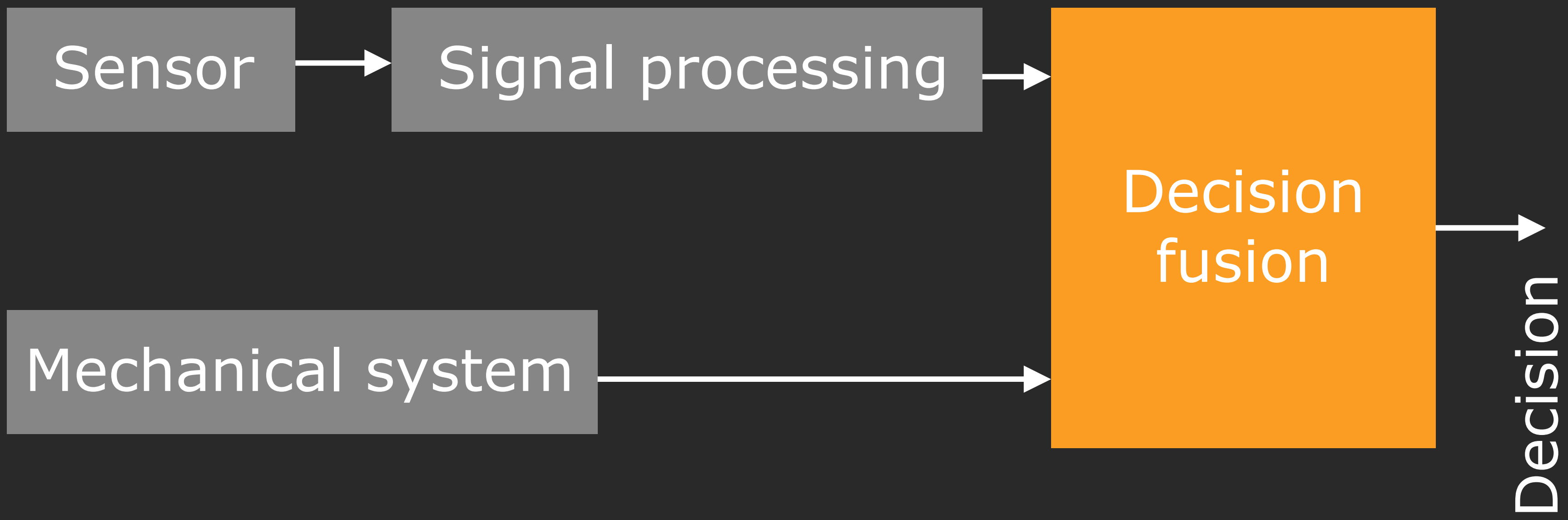


Improving performance by fusion of methods

- Methods (sensors, mechanical etc.) supplement each other by exploiting different aspect of physical environment



Late integration by decision fusion



Pros and cons

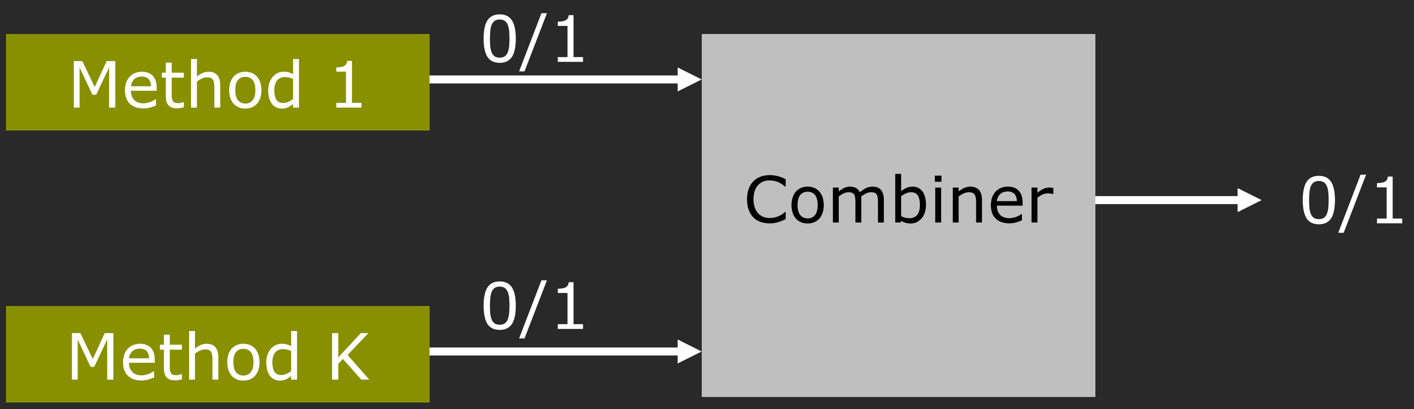
- ☺ Combination leads to a possible exponential increase in detection performance
- ☺ Combination leads to better robustness against changes in environmental conditions
- ☹ Combination leads to a possible linear increase in false alarm rate

Dependencies between methods

Contingency tables

Mine present		Method j	
		yes	no
Method i	yes	c11	c10
	no	c01	c00

Optimal combination



Optimal combiner depends on contingency tables

Optimal combiner

Method		Combiner						
1	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0
0	1	0	0	0	1	[illegible]	1	1
1	0	0	1	1	0	0	1	1
1	1	1	0	1	0	1	0	1

OR rule is optimal for independent methods

$2^{2^{K-1}} - 1$ possible combiners

OR rule is optimal for independent methods

Method 1:	1 0 0 1 0 0 1 0
Method 2:	0 1 0 0 1 0
Combined:	1 1 0 1 1

Independence to be confirmed by Fisher's test

$$P_d(OR) = P(\hat{y}_1 \vee \hat{y}_2 = 1$$

$$= 1 - P(\hat{y}_1 = 0 \wedge \hat{y}_2 = 0$$

$$= 1 - P(\hat{y}_1 = 0 \mid y = 1) \cdot P(\hat{y}_2 = 0 \mid y = 1)$$

$$= 1 - (1 - P_{d1}) \cdot (1 - P_{d2})$$

False alarm follows a similar rule

$$
\begin{aligned}
&P_{fa}(OR) = \\
&P(\hat{y}_1 \vee \hat{y}_2 = 1 \mid y = 0) \\
&= 1 - P(\hat{y}_1 = 0 \wedge \hat{y}_2 = 0 \mid y = 0) \\
&= 1 - P(\hat{y}_1 = 0 \mid y = 0) \cdot P(\hat{y}_2 = 0 \mid y = 0) \\
&= 1 - (1 - P_{fa1}) \cdot (1 - P_{fa2})
\end{aligned}
$$

Example

$$p_{d1} = 0.8, p_{fa1} = 0.1 \quad p_{d2} = 0.7, p_{fa2} = 0.1$$

$$p_d = 1 - (1 - 0.8) \cdot (1 - 0.7) = 0.94$$

$$p_{fa} = 1 - (1 - 0.1) \cdot (1 - 0.1) = 0.19$$

Exponential increase in detection rate

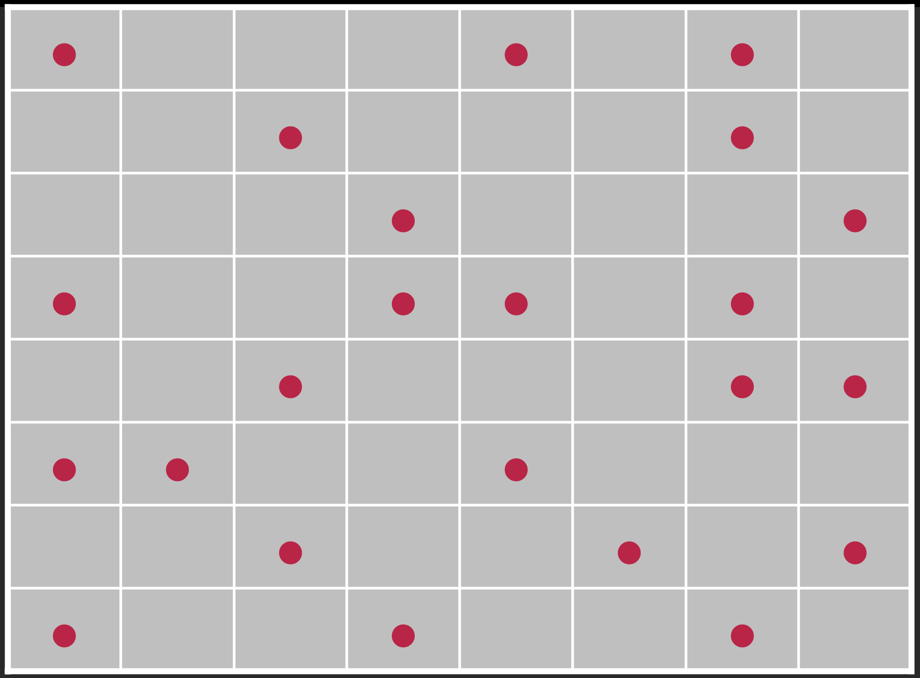
Linear increase in false alarm rate

Joint discussions with: Bjarne Haugstad

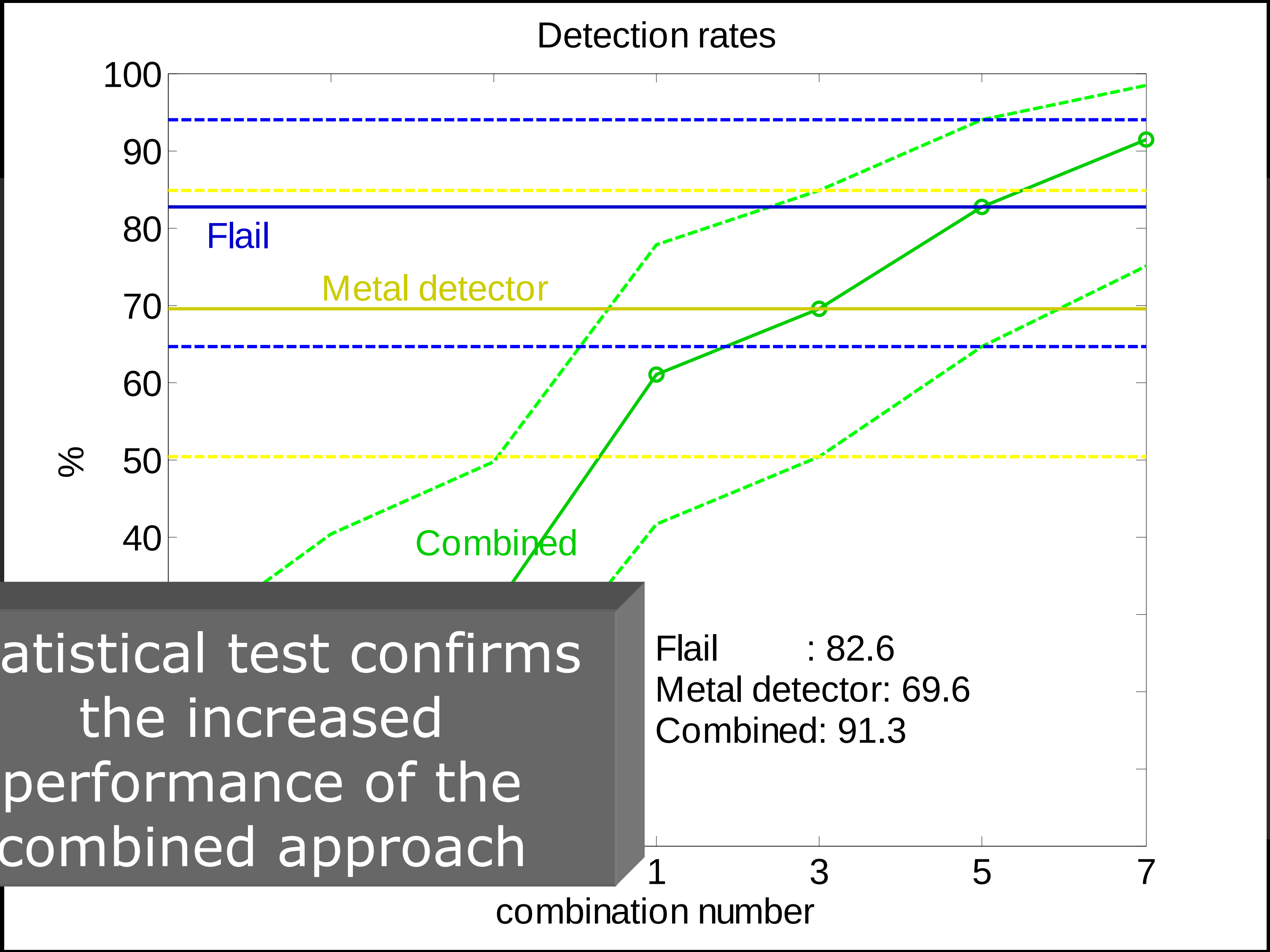
Artificial example

- N=23 mines
- Method 1: P(detection)=0.8, P(false alarm)=0.1
- Method 2: P n)=0.7, P(false alar
- Resolution:

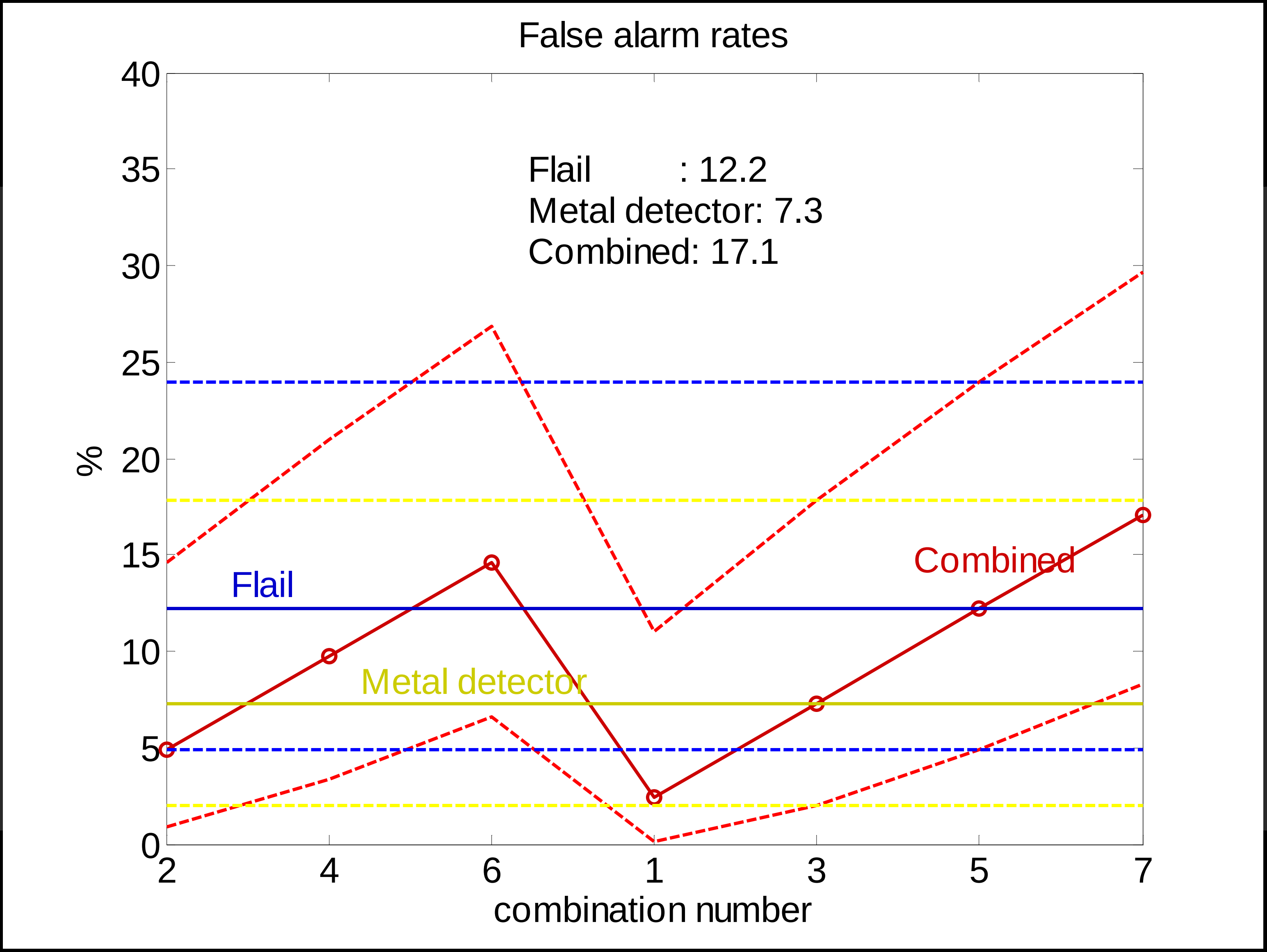
		True	
		yes	no
Estimated	yes	19	5
	no	4	36



Confusion table for method 1



Statistical test confirms the increased performance of the combined approach


False alarm rates
Flail : 12.2
Metal detector: 7.3
Combined: 17.1
Flail
Combined
Metal detector
%
combination number
0
5
10
15
20
25
30
35
40
2
4
6
1
3
5
7

Conclusions

- Statistical decision theory and modeling is essential for optimal use of prior information and empirical evidence
- It is very hard to assess the necessary high performance which is required to have a tolerable risk of casualty
- Combination of methods is a promising avenue to overcome current problems