



Centrum pro výzkum
toxických látek
v prostředí

BIOMARKERS AND TOXICITY MECHANISMS 01 - INTRODUCTION

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Tento projekt je spolufinancován Evropským sociálním fondem a státním rozpočtem České republiky.



INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

Course summary

1) Introduction

- Intro and overview of the mechanisms beyond the toxicity
(*with special respect to environmental contaminants*)
- Intro and concept of biomarkers

2) Details on selected important toxicity mechanisms

- Membrane toxicity, enzyme inhibitions, oxidative stress, genotoxicity, Nuclear Receptors (AhR, ER, AR) etc.
- Methods to determine toxicity mechanism

3) Biomarkers

- What it is and how to find (identify) suitable biomarker(s)?
- The overview of the most important biomarker classes
- Methods of biomarker assessment

Suggested reading and other study materials

The content of this class was prepared as a blend of principles of pharmacology, mechanistic (eco)toxicology and effect biomarkers. The content is not reflected in one single textbook.

All slides and presentations are available in IS MUNI

Video records from the lectures are also available in IS

Additional reading is not necessary ... following books and materials could be recommended:

VAN GESTEL, K. et al. (2021) Environmental Toxicology, an open online textbook.

2021. [URL info](#)

Newman (2020) Fundamentals of Ecotoxicology (ISBN: 978-0-8153-5402-4) – chapters 6-9.

Also available in MUNI Campus Library:

<https://katalog.muni.cz/Record/MUB01006503461>

Additional popular reading (Environmental toxicology):

https://en.wikipedia.org/wiki/Silent_Spring

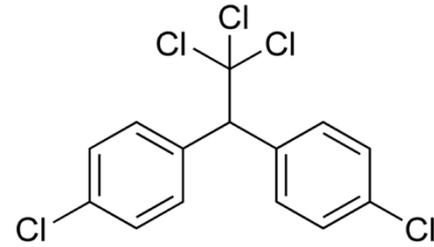
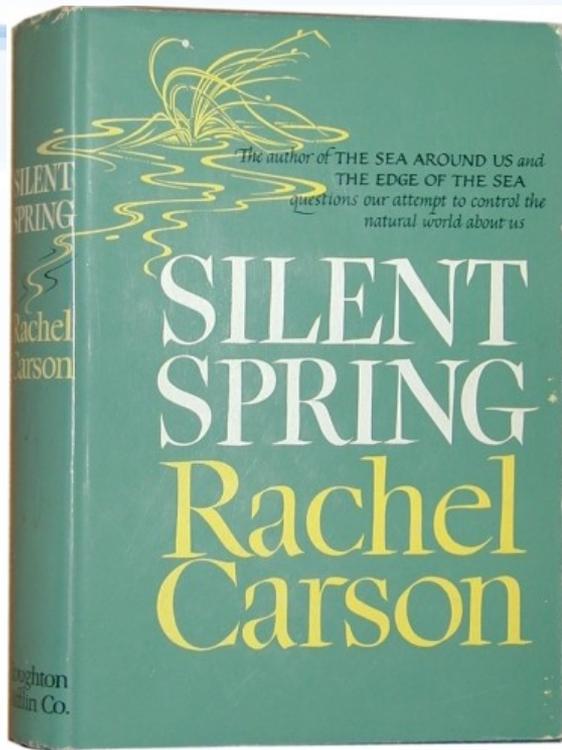
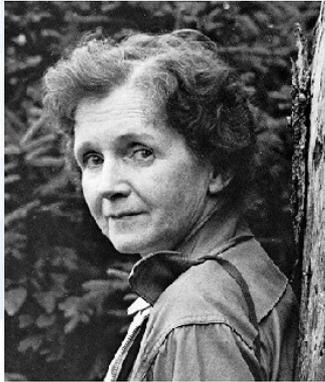
https://en.wikipedia.org/wiki/Our_Stolen_Future



The importance of understanding toxicity mechanisms



1962



© Patuxent Wildlife Refuge, MA, USA

"DDT is good for me-e-e!"

The great expectations held for DDT have been realized. During 1946, exhaustive scientific tests have shown that, when properly used, DDT kills a host of destructive insect pests, and is a benefactor of all humanity.

Pennsalt produces DDT and its products in all standard forms and is now one of the country's largest producers of this amazing insecticide. Today, everyone can enjoy added comfort, health and safety through the insect-killing powers of Pennsalt DDT products . . . and DDT is only one of Pennsalt's many chemical products which benefit industry, farm and home.

GOOD FOR STEERS—Beef grows meatier nowadays . . . for it's a scientific fact that—compared to untreated cattle—beef steers gain up to 50 pounds extra when protected from horn flies and many other pests with DDT insecticides.

KNOW FOR THE HOME—helps to make healthier, more comfortable homes . . . protects your family from dangerous insect pests. Use Knox-Out DDT Powders and Sprays as directed . . . then watch the bugs "bite the dust"!

GOOD FOR FRUITS—Bigger apples, juicier fruits that are free from unsightly worms . . . all benefits resulting from DDT dusts and sprays.

KNOW FOR DAIRIES—Up to 20% more milk . . . more butter . . . more cheese . . . tests prove greater milk production when dairy cows are protected from the annoyance of many insects with DDT insecticides like Knox-Out Stock and Barn Spray.

GOOD FOR ROW CROPS—25 more barrels of potatoes per acre . . . actual DDT tests have shown crop increases like this! DDT dusts and sprays help truck farmers pass these gains along to you.

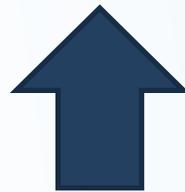
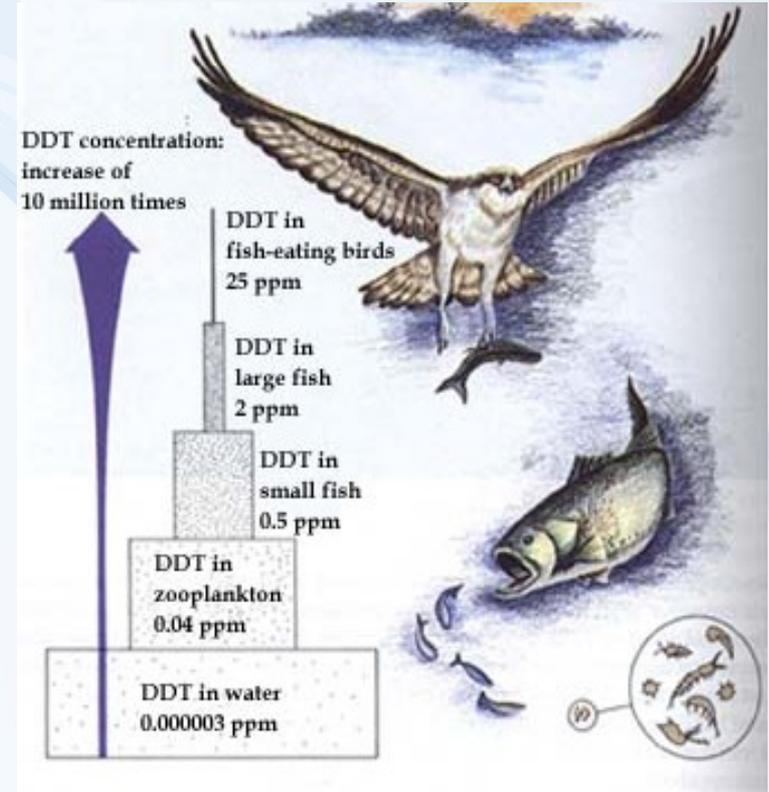
KNOW FOR INDUSTRY—Food processing plants, laundries, dry cleaning plants, hotels . . . dozens of industries gain effective bug control, more pleasant work conditions with Pennsalt DDT products.

PENN SALT
CHEMICALS
57 Years' Service to Industry • Farm • Home
PENNSYLVANIA SALT MANUFACTURING COMPANY
WIDENER BUILDING, PHILADELPHIA 7, PA.

In vivo: shell thinning

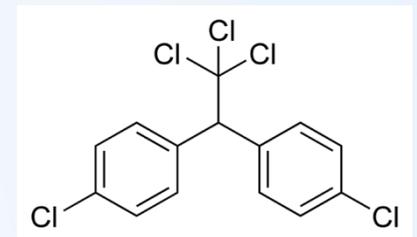


In situ: bioaccumulation -> **bird population decline**

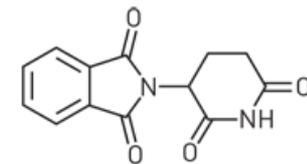


Biochemistry discovered in 1970s:
Bird carbonate dehydratase

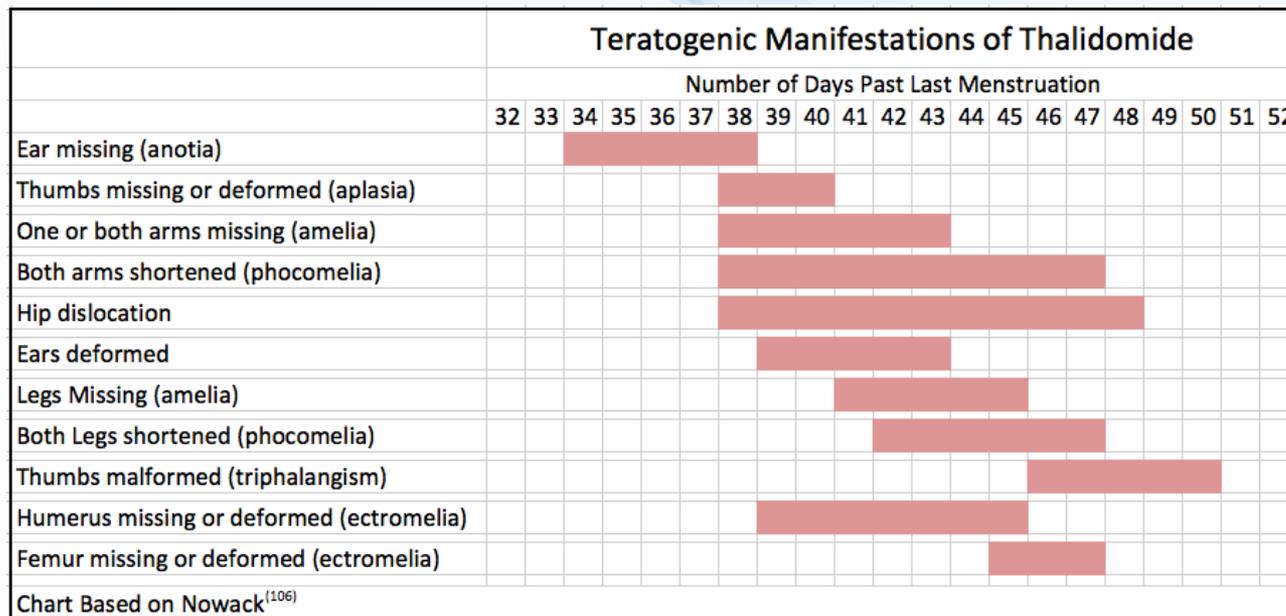
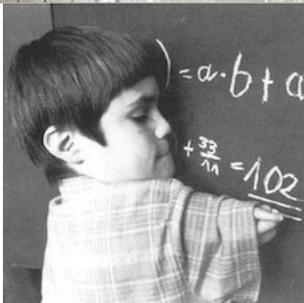
Bitman et al. *Science* 1970,
168(3931): 594



Thalidomide



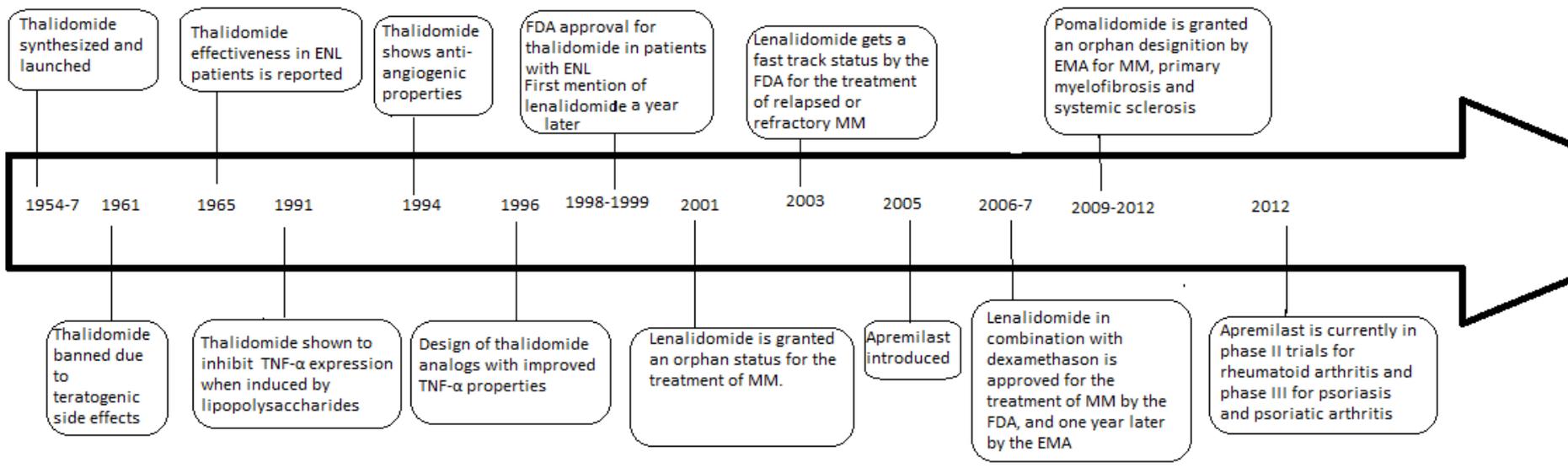
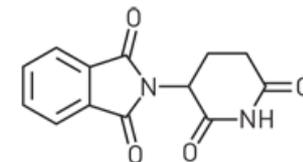
- Originally marketed in 1957 as sedative / hypnotic
 - also curing anxiety, gastritis, tension
 - against nausea and morning sickness of pregnant
 - TERATOGENICITY → Development of phocomelia = limb malformations (10 000 children worldwide / 40% survived)



- Currently still in use - completely different targets
 - : anticancer (multiple myeloma), antileprosis, immunosuppression

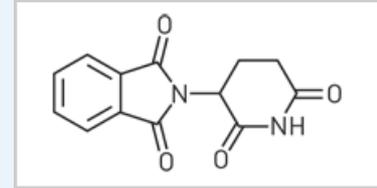


Thalidomide



Thalidomide

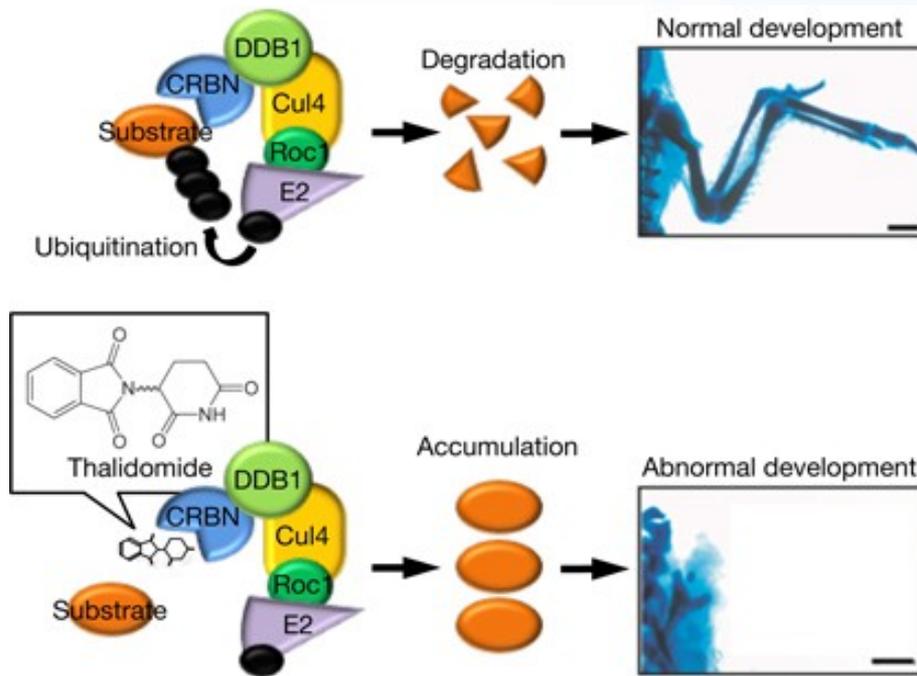
... mechanisms of action



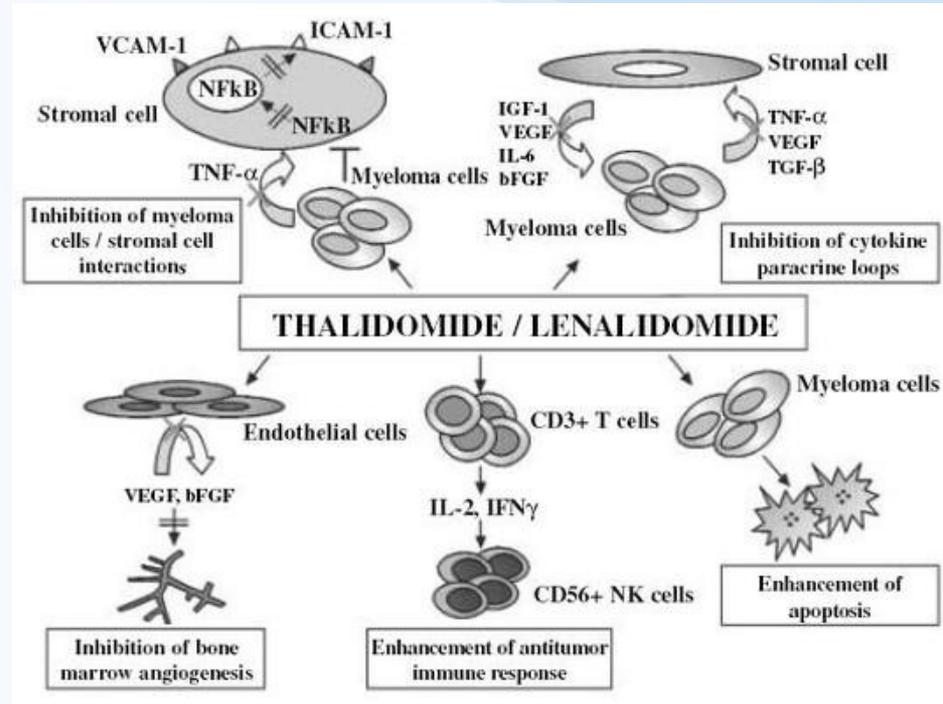
(1) Sedative effects

... mechanism unknown

(2) Teratogenicity

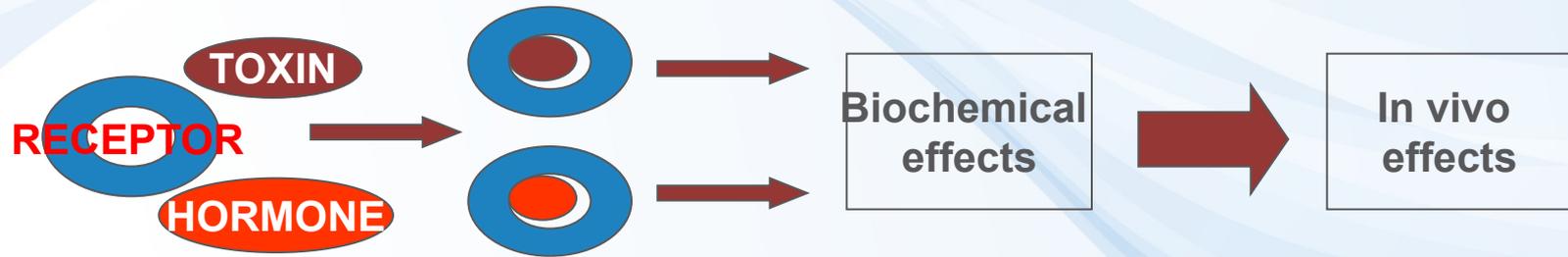


(3) Anticancer



MECHANISMS of chronic toxicity

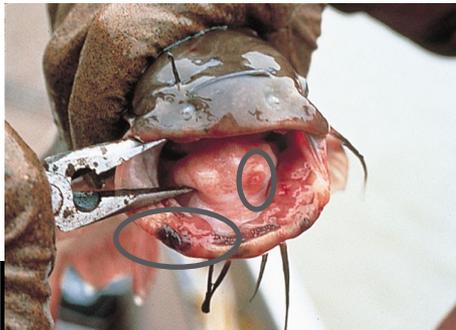
- Various chronic effects have uniform biochemical basis



- principle studies with mechanistically based *in vitro* techniques
- estimation of *in vitro* effects of individual compounds

Understanding MoA ... may predict higher-level effects

Organism



Population & beyond



Basics and keywords from toxicology



Toxicity - concept

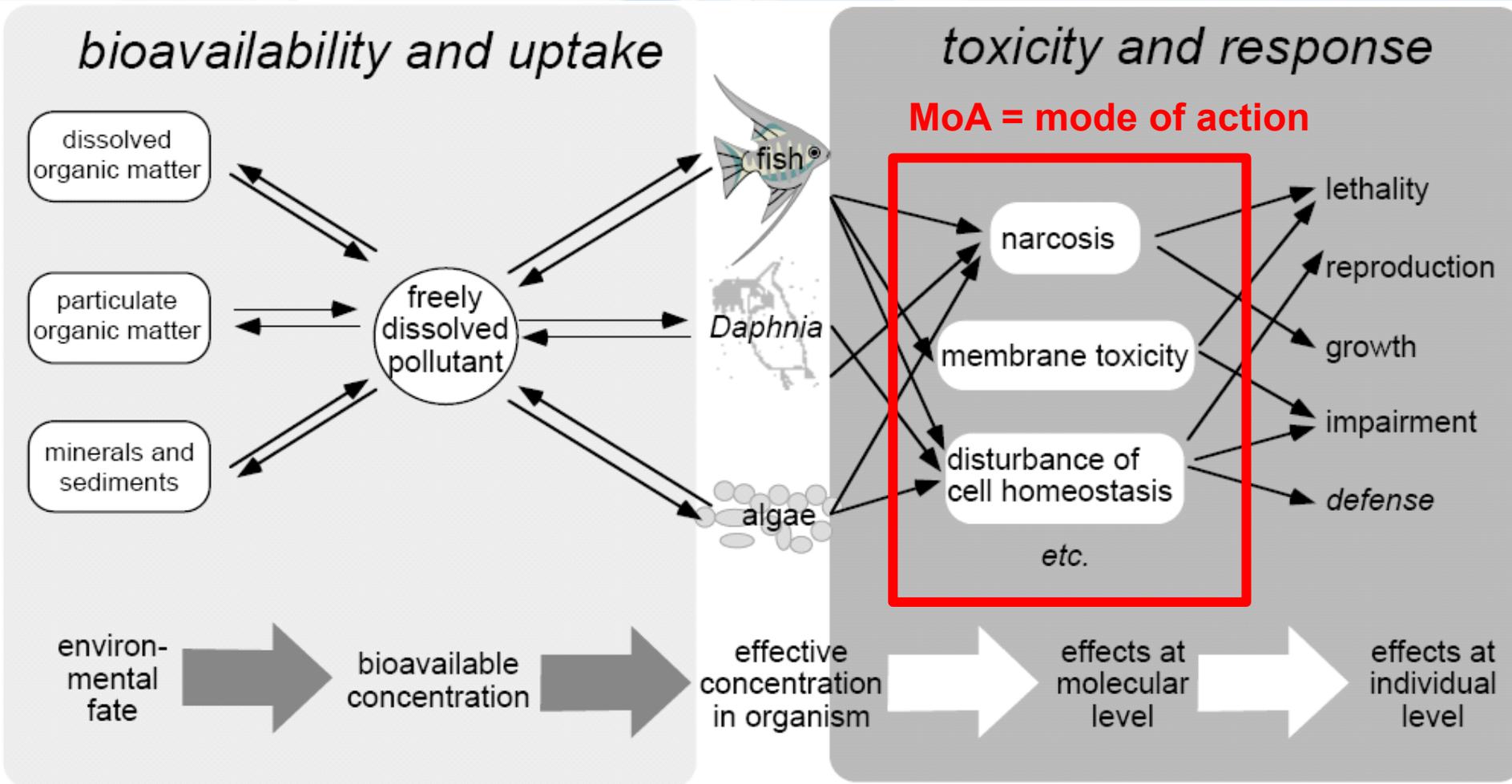


Figure 1 The effective concentration of a pollutant in an organism (e.g. fish, daphnia, algae) or at the target site inside the organism is the link between the environmental fate of a pollutant and its toxic effect.



From mechanisms (or modes of action) to biomarkers

- Chemical enters organism
+ may be metabolized/detoxified,
transported, released ...

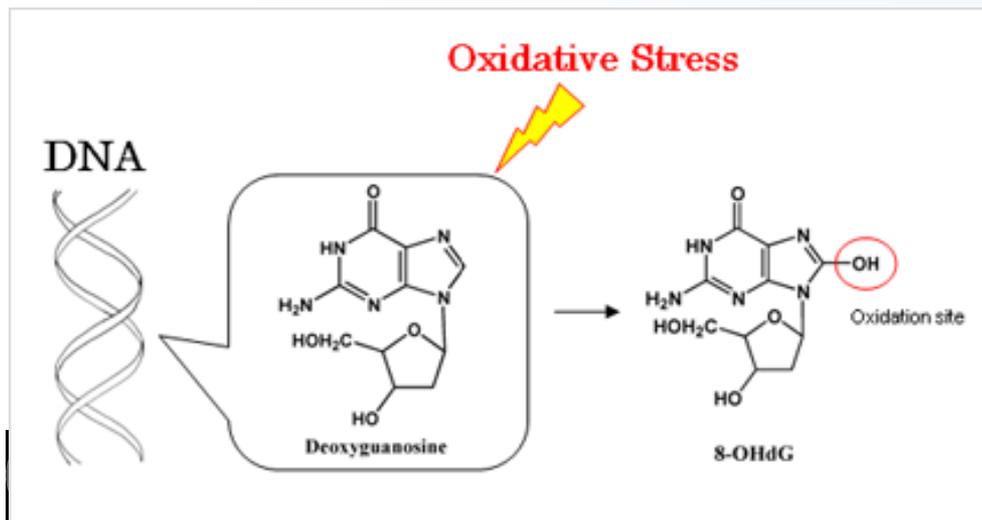
→ **Toxicokinetics**

- Chemical reacts with target (e.g. DNA) and changes a specific nucleotide (e.g. G → de-oxo-G)

→ **Toxicodynamics**

= **toxicity mechanisms (MoA)** and following **toxic effects** (e.g. mutation, cancer ...)

- Elevated **de-oxo-G** in blood



→ **(Selective) biochemical marker (biomarker)**
= information about exposure and/or effect

Toxicity – the cause-effect paradigm

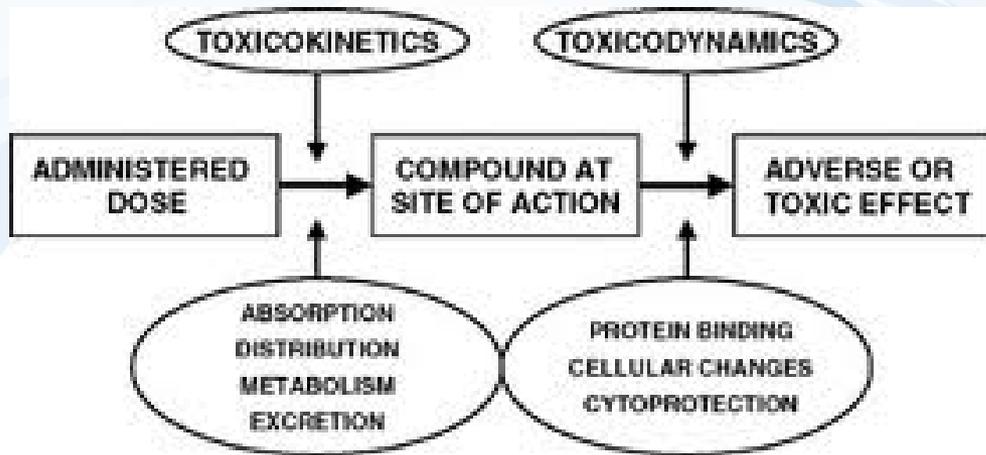
Paracelsus (1493 - 1541)



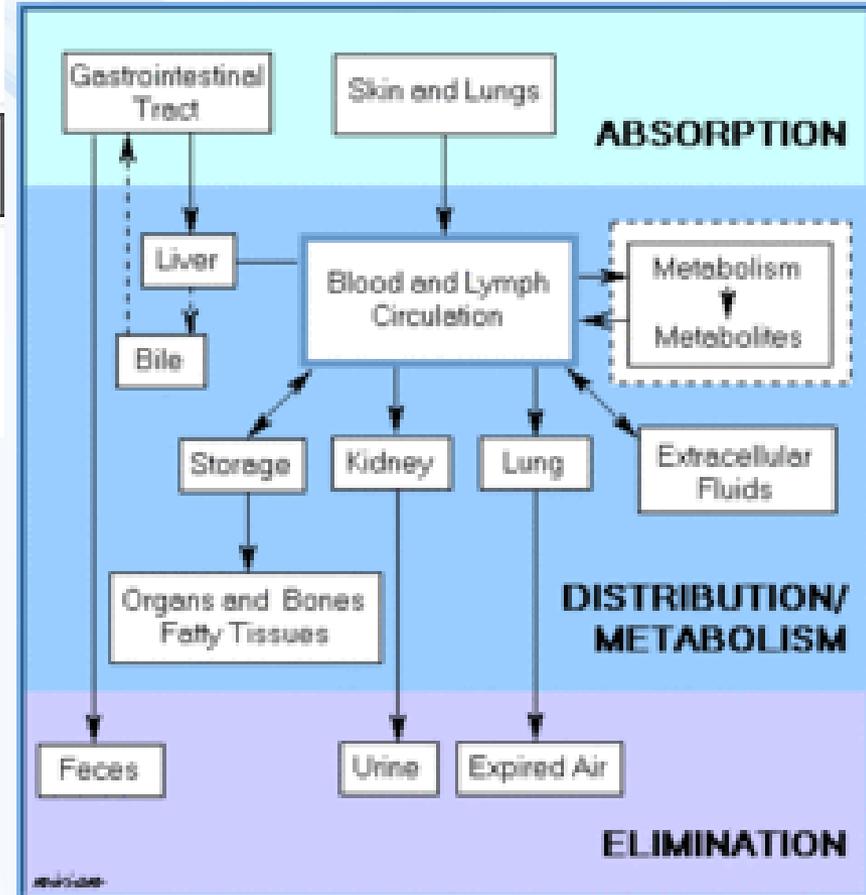
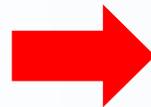
- ‘What is there which is not a poison?’
- All things are poison and nothing without poison.
 - Solely the dose determines that a thing is not a poison.
 - *Toxicology – the science of doses*



What processes are beyond toxicokinetics?



ADME



Toxicokinetics ...

... EXPOSURE phase → Determines the final dose

Toxicokinetics in fish

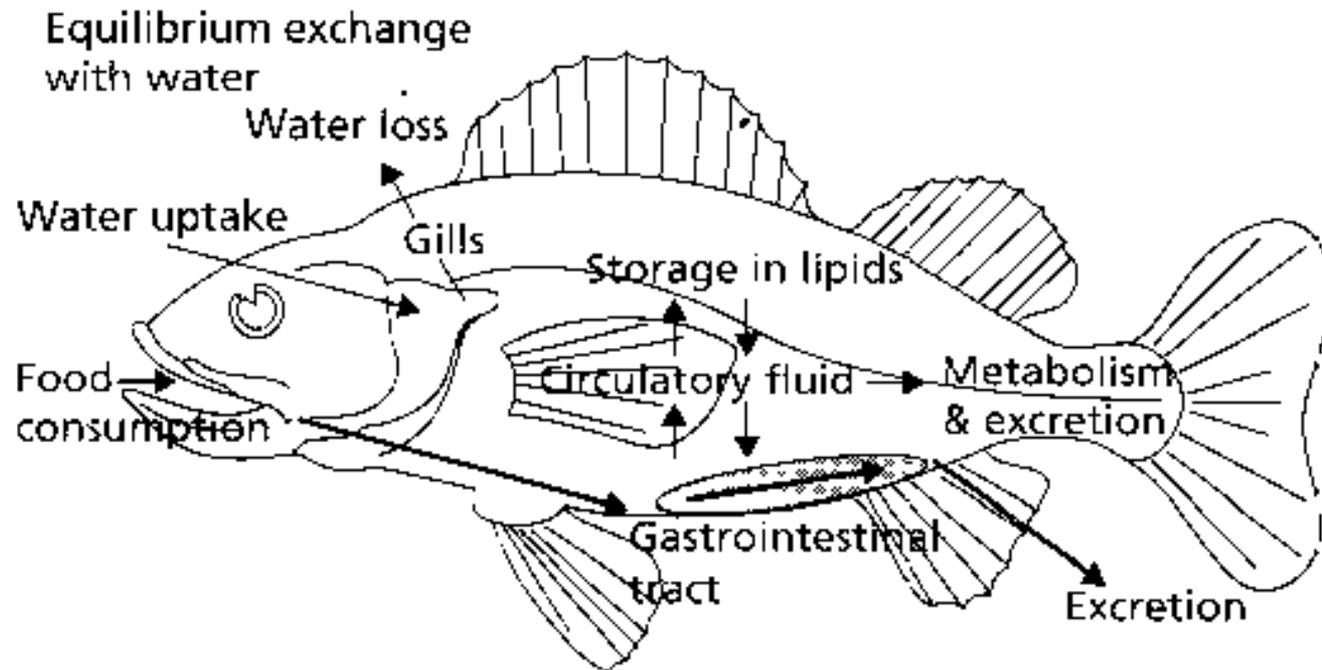
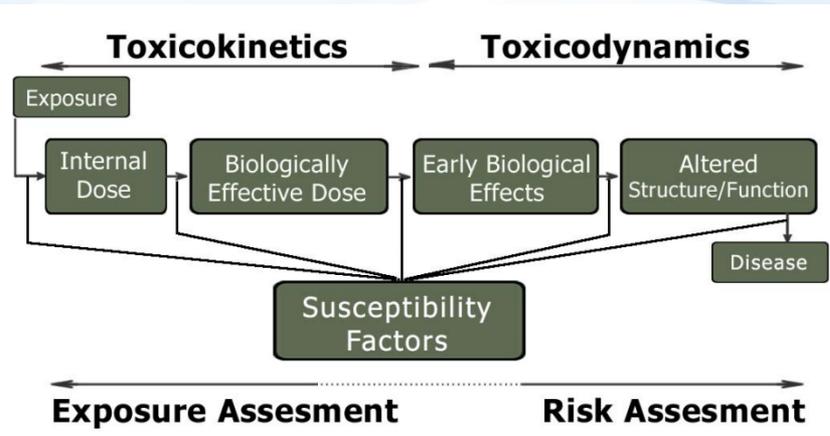
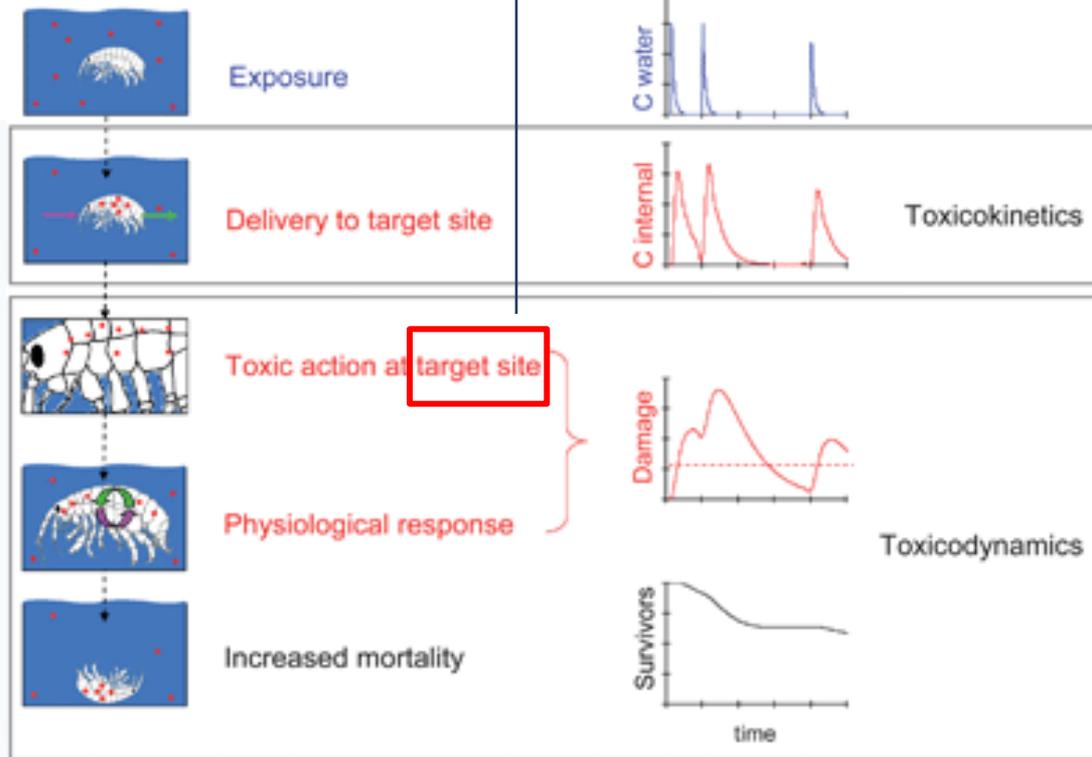


Fig. 3.5 Uptake, accumulation and loss processes for a toxicant in the ambient water with fish.

ToxicoDYNAMICS



TARGETS = macromolecules
(DNA/RNA, proteins, membrane lipids)



MoA



... and measurable
EFFECTS



What is toxicity? What are the types of effects?

- **Toxicity**
 - degree to which a substance (at certain dose) can damage an organism
- **Exposure & toxicity**
 - **acute** (immediate, high doses, days)
 - **chronic** (sublethal / low doses, long-term)
- **Effect & toxicity**
 - **lethal (acute)**
 - mortality – definitive endpoint / high doses
 - easy to determine (single endpoint – death)
 - **nonlethal, sublethal (chronic)**
 - endocrine disruption, reproduction toxicity, immunotoxicity, tumor induction etc.
 - difficult to determine (multiple endpoints)
 - more specific – low concentrations / longer exposures
 - **often reflected by specific biochemical changes (biomarkers)**
- **Systems and organ & toxicity**
 - Systemic lethal toxicity
 - Organ-specific toxicity (neurotoxicity, hepatotoxicity, nephrotoxicity ...)
 - Developmental toxicity
 - Reproduction toxicity



Principles of toxicity testing

- 1) Define and know **biological target** (molecule, cell, organism, population) and its properties
- 2) Define and know **chemical** and its properties
- 3) **Define exposure** of biological system to a chemical
 - variable concentrations
 - defined or variable duration (time)
 - conditions (T, pH, life stage)
- 4) **Assess effects**, i.e. Changes in measurable parameter in relationship to variable doses
- 5) **Dose-response evaluation** & estimation of the toxicity value (i.e. concentration or dose):
LD_x, IC_x, EC_x, LOEC/LOEL, MIC ...



Effect assessment - procedure

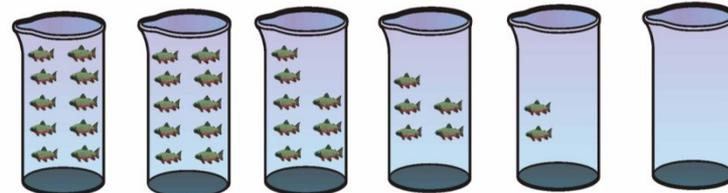


Cu addition



Concentration:

0.0 $\mu\text{g/L}$ 13 $\mu\text{g/L}$ 25 $\mu\text{g/L}$ 50 $\mu\text{g/L}$ 100 $\mu\text{g/L}$ 200 $\mu\text{g/L}$



Control 1 2 3 4 5

96-hour LC50 = 50 $\mu\text{g/L}$

Effect concentrations expressed in total/dissolved Cu



How to study (chronic) toxicity ?

- **In vitro studies (biochemical mechanisms)**

- + easy to perform, short-term
- + highly controlled conditions
- + lower amounts of chemicals needed
(new cmpnds screening)

- ecotoxicological relevancy
- mostly with vertebrate cells

- **In vivo biotest testing**

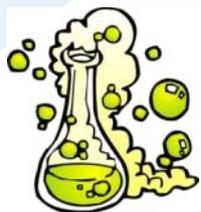
- + unique whole organisms
- + controlled conditions
- + better ecological interpretation

- only few (ecologically nonrelevant) organisms used
- mostly ACUTE assays
- chronic: long exposures

- **Field and *in situ* observations, epidemiological studies**

Hazard assessment

Traditionally – Evaluation of adverse effects using the whole organism models



Chemical



Organism



Adverse Effects

Death
Altered Reproduction
Inhibition of Growth

Tumorigenicity
Skin irritation

...

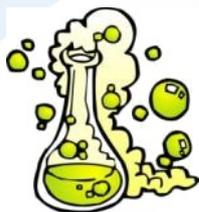


**REGULATORY FOCUS
(APICAL ENDPOINTS)**



Hazard assessment

Traditionally – Evaluation of adverse effects using the whole organism models



Chemical



Organism



Adverse Effects
Death
Inhibition of Growth
Altered Reproduction
Tumor
Skin irritation
...

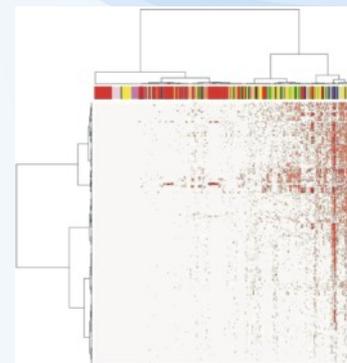
New – Ex vivo / in vitro / In chemico / In silico Methods



10^4 Chemicals

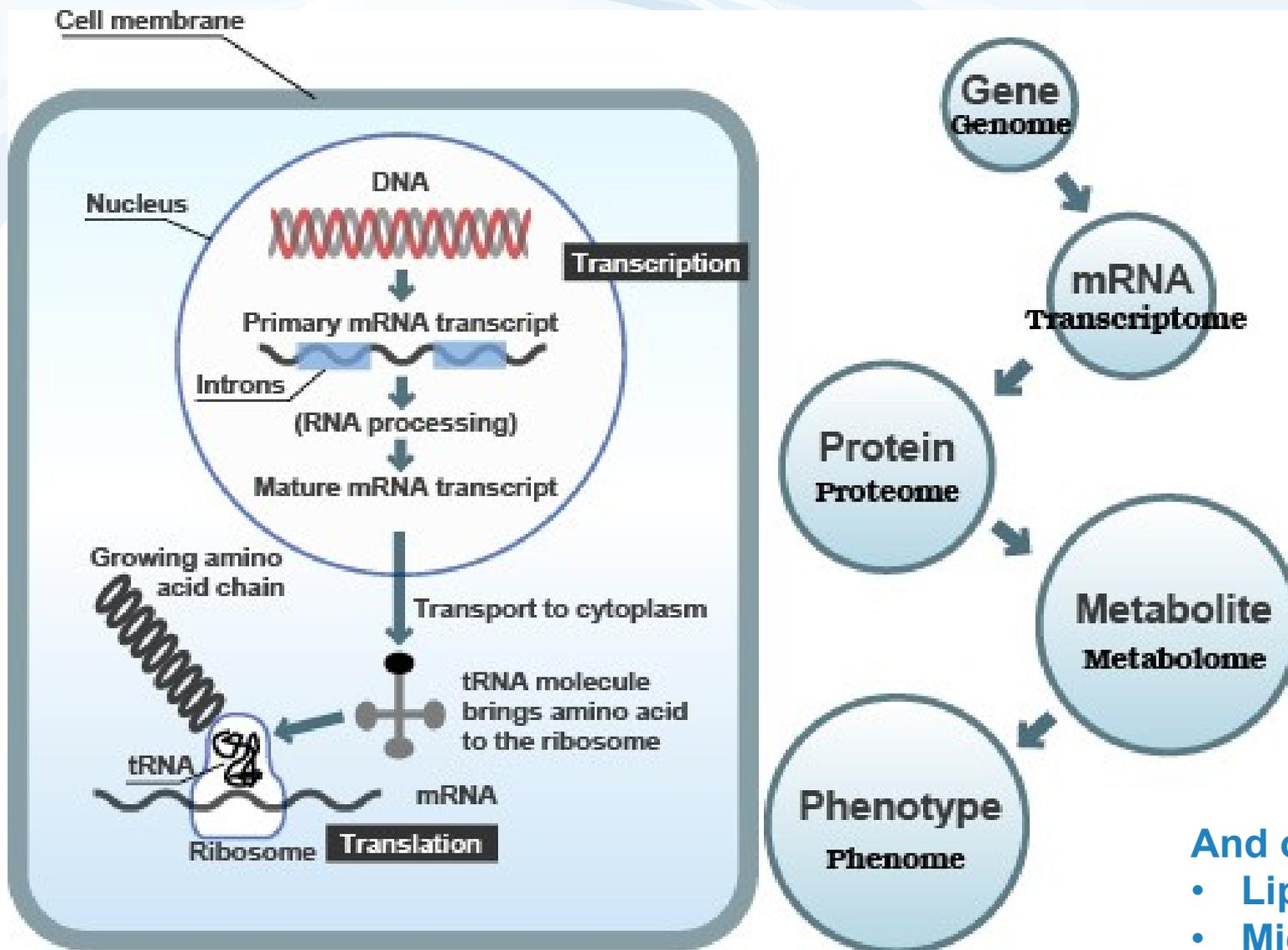


HTS
High-Throughput-Screening



**Chemical-biological interactions,
Mechanistic Toxicological Data**

Mode of Action (omics) toxicity testing



And other „omes“

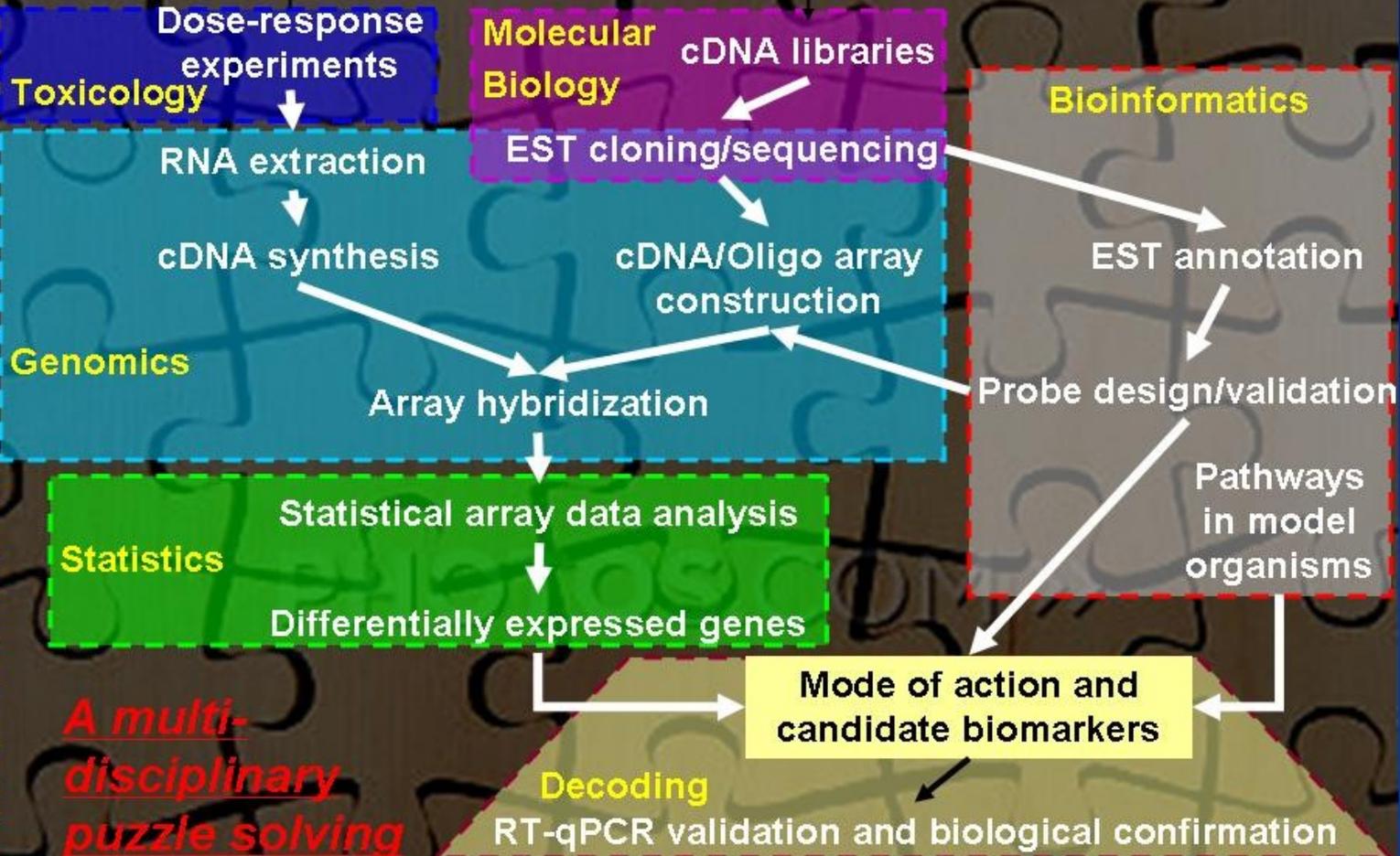
- Lipidome
- Microbiome ...

Omes is not only for humans ...

Earthworm Toxicogenomics



US Army Engineer Research & Development Center



A multi-disciplinary puzzle solving exercise

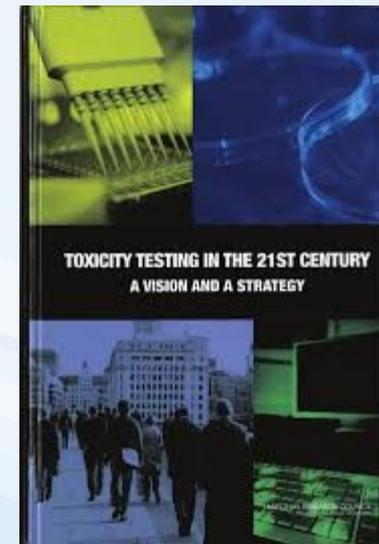
One Team, One ERDC . . . Relevant, Ready, Responsive, Reliable

MoA and omics are supported by strategic documents & organizations

Toxicity Testing in the 21st Century: A Vision and a Strategy

US National Academies of Sciences

<http://www.nap.edu/catalog/11970.html>



United States Environmental Protection Agency

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Key Links

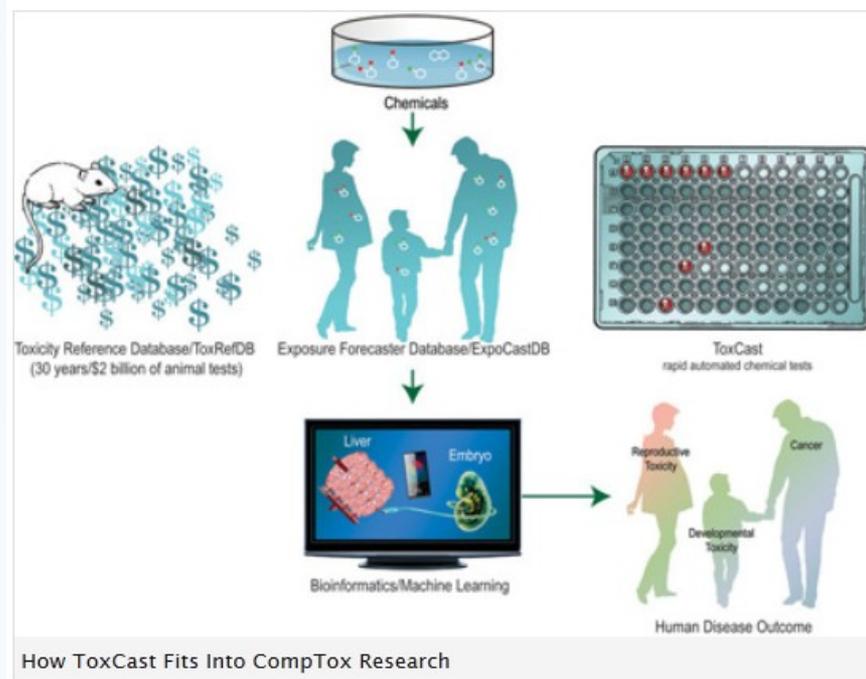
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[Basic Information](#)
[Organization](#)

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ToxCast™

Screening Chemicals to Predict Toxicity Faster and Better



Hazard assessment

Traditionally – Evaluation of adverse effects using the whole organism models



Chemical



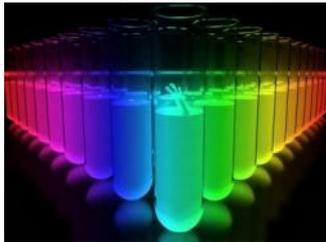
Organism



Adverse Effects
Death
Inhibition of Growth
Altered Reproduction
Tumor
Skin irritation
...



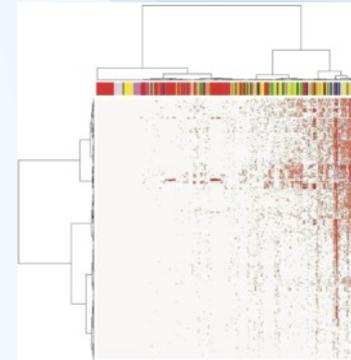
New – Ex vivo / in vitro / In chemico / In silico Methods



10^4 Chemicals



HTS
High-Throughput-Screening

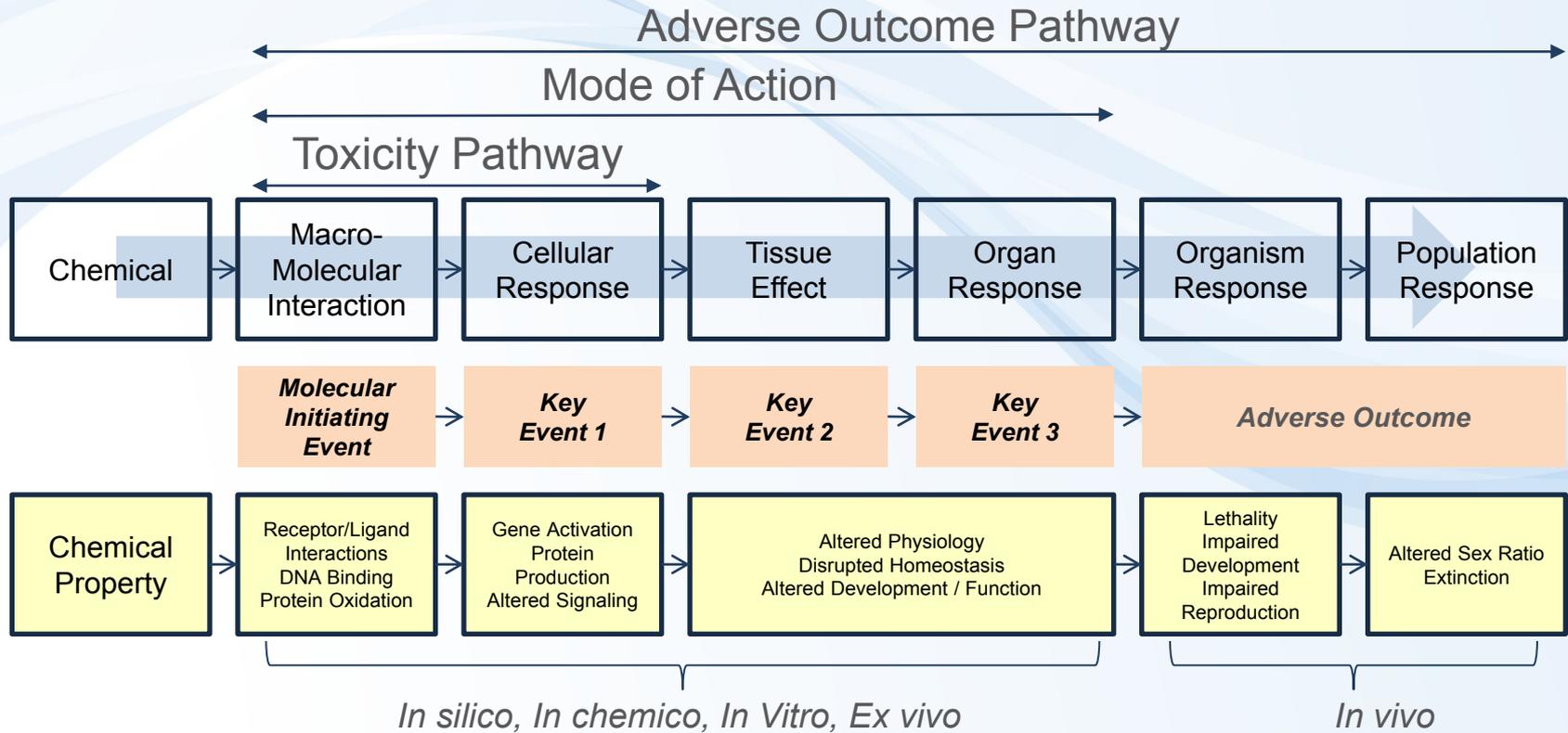


**Chemical-biological interactions,
Mechanistic Toxicological Data**

Key task/question:

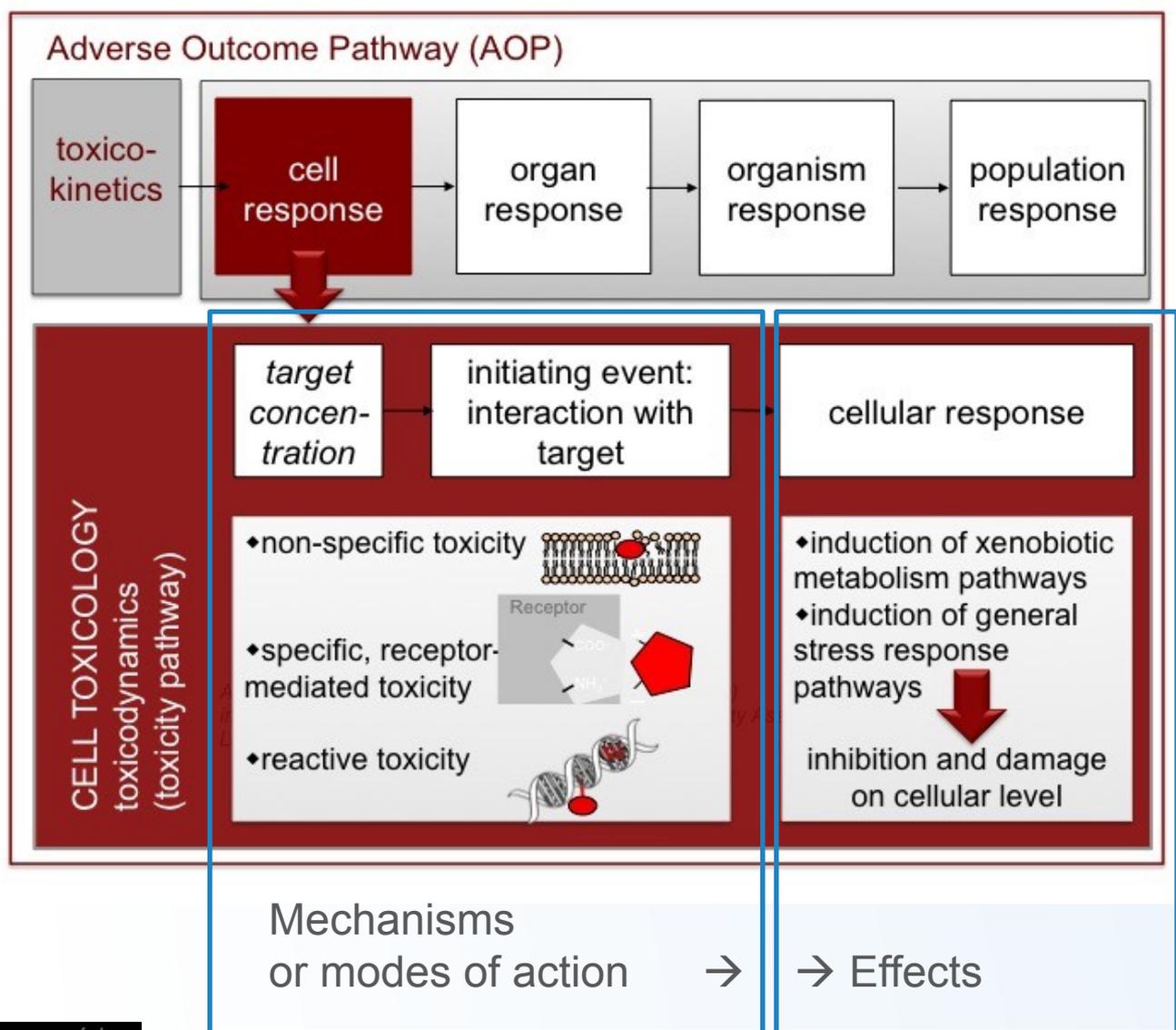
How to link MECHANISTIC INFORMATION with APICAL ENDPOINTS ?

Adverse Outcome Pathways



The **EXISTING KNOWLEDGE** is used **to link the** two anchor points:
Molecular Initiating Event (MIE) and **Adverse Outcome (AO)**
via a series of intermediate steps: **Key Events**

Concept of “Adverse Outcome Pathway” (AOP)



AOP = Global strategy with support from OECD, EU, USA



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- > Biosafety - BioTrack

Adverse Outcome Pathways, Molecular Screening and Toxicogenomics

WHAT'S NEW

SURVEY ON ADVERSE OUTCOME PATHWAYS (AOPS) TO IDENTIFY DEVELOPMENT PRIORITIES

The OECD has launched a survey to explore the utility of AOPs for regulatory assessment of chemicals and to identify development priorities. The objective is to collect feedback on how the AOP concept and/or existing AOPs are already being used for regulatory purposes, to understand where they fall short regarding their utility, and to identify what directions and priorities future AOP development work should embrace to increase their impact on regulatory toxicology and chemical risk assessment.

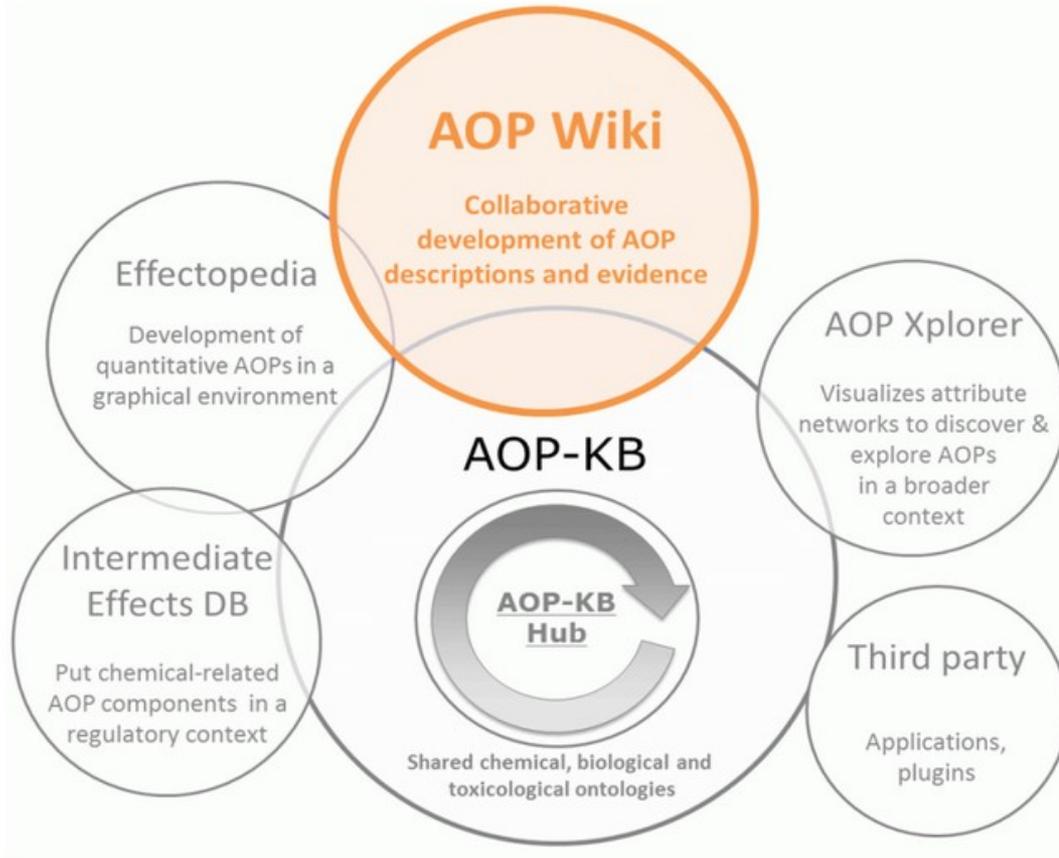
The survey is mainly for chemical safety regulators who are experiencing a transition in their work towards an increased use of 'alternative' methods and AOPs. However, stakeholders that come from the regulated community and environmental NGOs are also welcome to participate.

> **The survey is now closed. Thank you for your submissions.**

<http://www.oecd.org/chemicalsafety/testing/projects-adverse-outcome-pathways.htm>



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Please click on any of the AOP-KB elements you want to use.

Please note that the AOP-KB is work in progress and more elements will become available over time.

<http://aopkb.org/>

Key documents

OECD Guidance document and a template for developing and assessing adverse outcome pathways (Series No. 184, Series on Testing and Assessment)

Handbook for AOP developers

AOP Wiki

- https://aopkb.org/aopwiki/index.php/Main_Page
- Wiki-based platform for development of AOPs
- Only members of an OECD AOP development project can create / edit AOPs



What AOPs are in AOP Wiki – Sept 2022 ?



OECD Endorsed (WNT and TFHA)	22	<ul style="list-style-type: none"> Alkylation of DNA in male pre-meiotic germ cells leading to heritable mutations Aromatase inhibition leading to reproductive dysfunction
EAGMST Under Review & for comments	22	
EAGMST Under Development	71	
AOPs Under Development	Ca 250+	

- Total 409 AOPs**

- OECD Extended Advisory Group on Molecular Screening and Toxicogenomics (EAG MST)
- The Working Group of the National Coordinators of the Test Guidelines Programme (WNT)

AOP Example: MIE aromatase inhibition

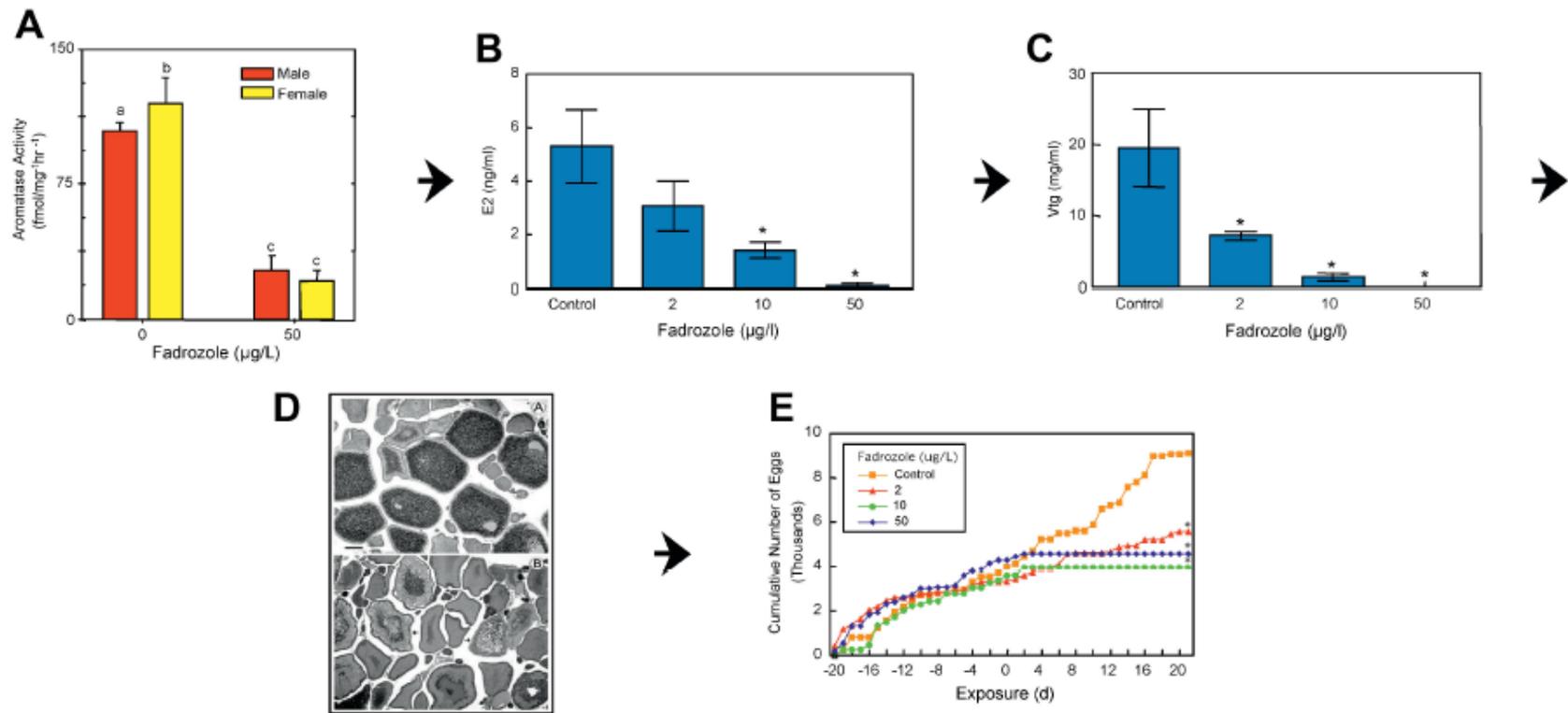


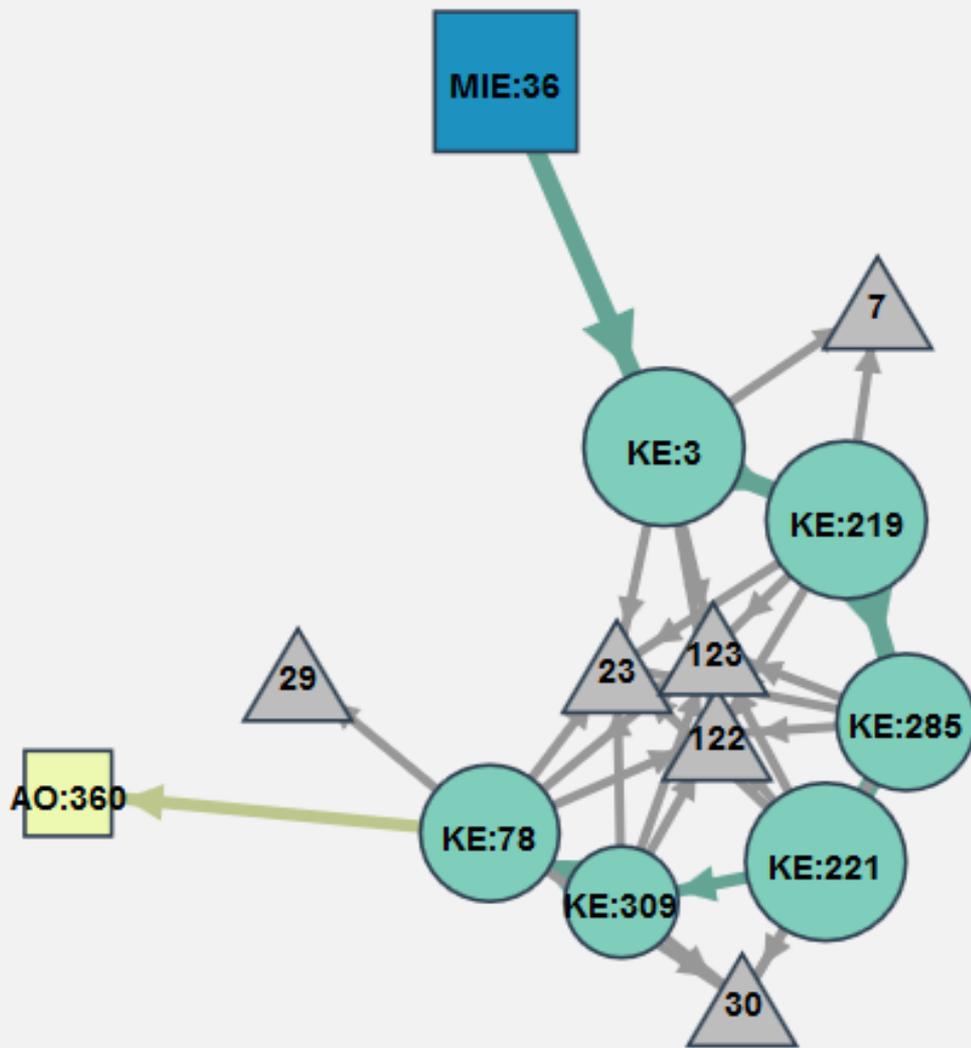
Fig. 3. An adverse outcome pathway in fish [2,50]. Aromatase inhibitor example. (A) Aromatase inhibition by fadrozole; (B) Reduction in circulating estradiol; (C) Reduction in circulating vitellogenin (Vtg); (D) Histopathology of ovarian tissue, top panel normal ovary, bottom panel fadrozole treated; note oocyte atresia; (E) Adverse outcome on egg production–fecundity (© Elsevier, Used with permission),

Environmental Toxicology and Chemistry, Vol. 30, No. 1, pp. 64–76, 2011



Aromatase inhibition leading to reproductive dysfunction (in fish)

<https://aopwiki.org/wiki/index.php/Aop:25>



MIE



KE



AO



Other AOP including this KE



Indirect relationship



Direct relationship



*Size of node reflects essentiality of event

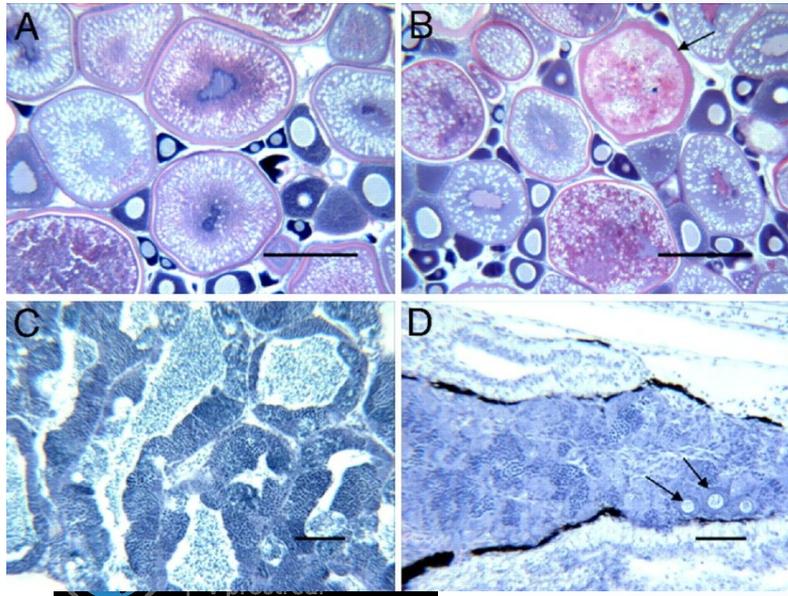
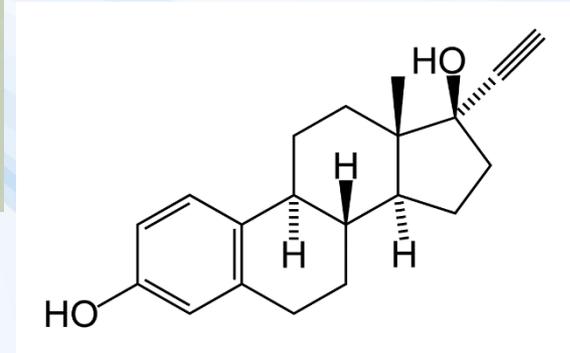
*Width of line reflects strength of evidence for relationship



Kidd, K.A. et al. 2007. **Collapse of a fish population** following exposure to **a synthetic estrogen**. *Proceedings of the National Academy of Sciences* 104(21):8897-8901

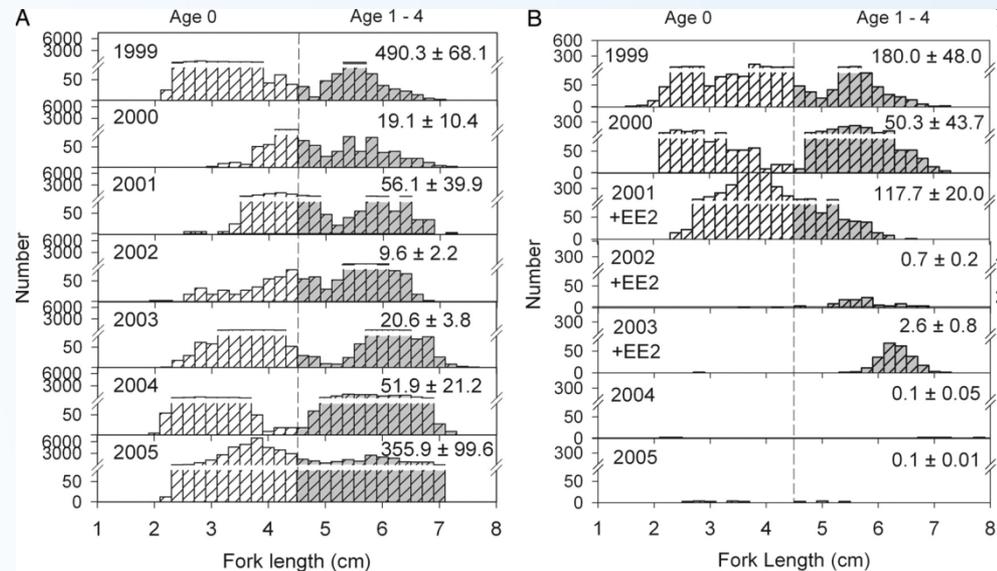


5 ng/L (!)
7 years



Controls

+Ethinylestradiol



Keywords to remember and understand

- What is meant by the “mechanism of action” (or “mode of action”) in toxicology?
- Why is it necessary to understand MoAs? What is the AOP concept?
- What is toxicokinetics? What is ADME?
- What is toxicodynamics?
- What is the relationship between the exposure and the effect?
- What are the different types of toxicity?
- How can the (toxic) effect be measured / assessed?
- What types of “bioassays” are available to study toxicity and/or MoA?
- How is the result (i.e. „toxicity“) described in numbers?