Multidisciplinary Design Optimization (MDO): Its Roots and Engineering Design Process Context

Jaroslaw Sobieski
Distinguished Research Associate
NASA Langley Research Center
Research and Technology Directorate
Hampton, Virginia, U.S.A,

Seminar at MIT
April 28, 2010

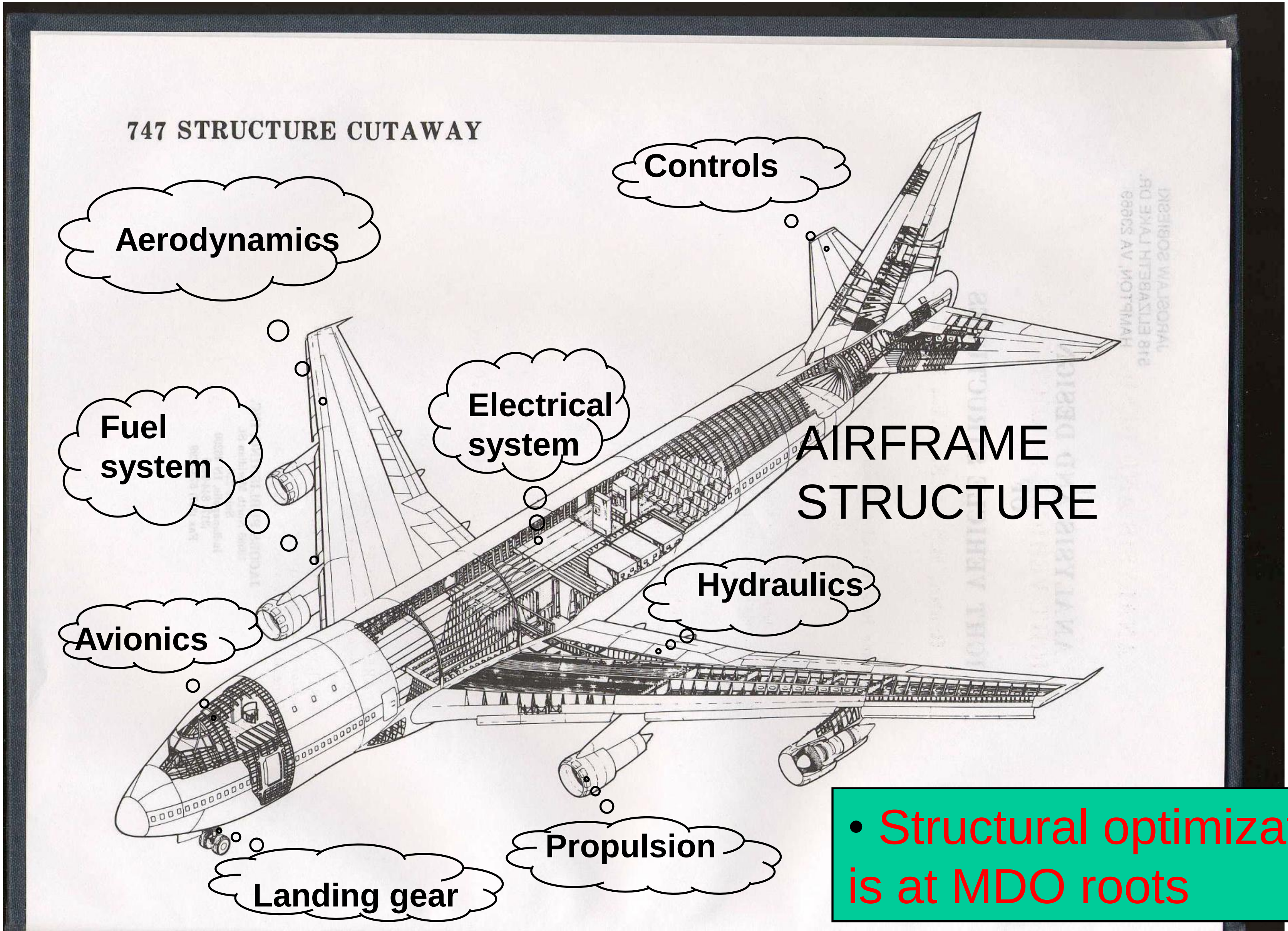
Presentation Plan

- Background, roots, and history

- MDO as a way to make design task manageable
    - System sensitivity
    - Organization of Information
    - Decomposition: Bi-Level Integrated System Synthesis (BLISS)

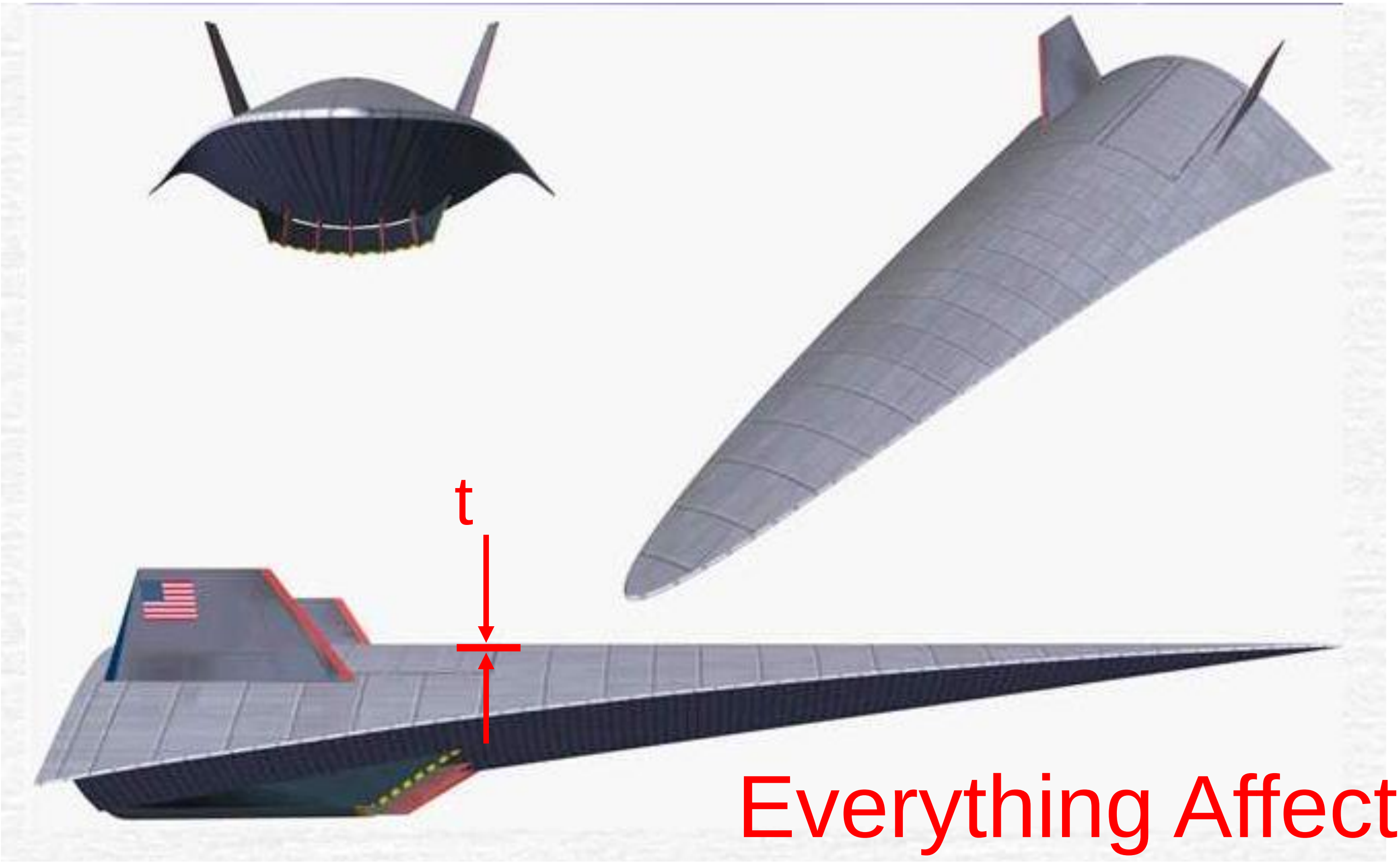
- MDO Assessment
    - Can do now well
    - Capabilities deficient, as yet
    - Avenues of development

In Vehicle Everything Couples to Structure



- Structural optimization is at MDO roots

Hypersonic Aircraft: Example of Coupling in Extreme



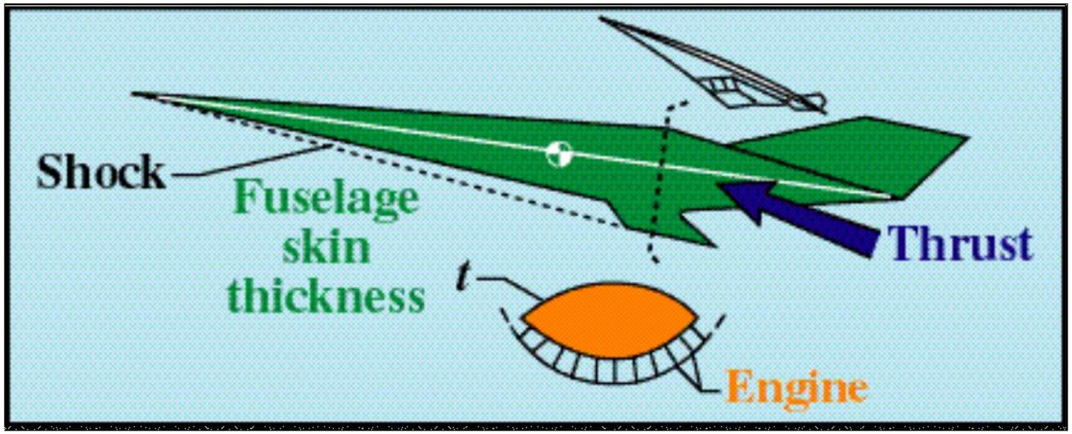
Everything Affects Everything Else

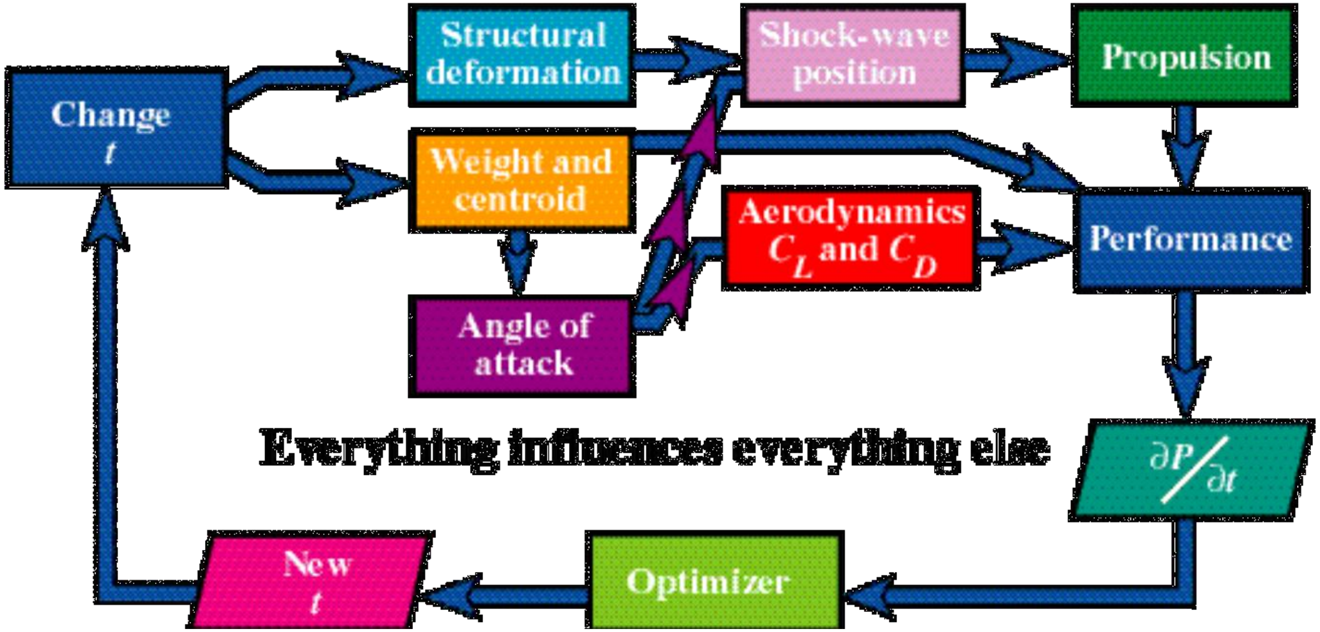
- What If: fuselage skin thickness is increased;
  how will the flight range change?

- Answer engages at least four disciplines:
  Aerodynamics, Structures, Control, Performance

Example of an MDO Problem

Simple Design Change – A Complex Chain of Influences





Change t

Structural deformation

Weight and centroid

Angle of attack

Shock-wave position

Aerodynamics C_L and C_D

Propulsion

Performance

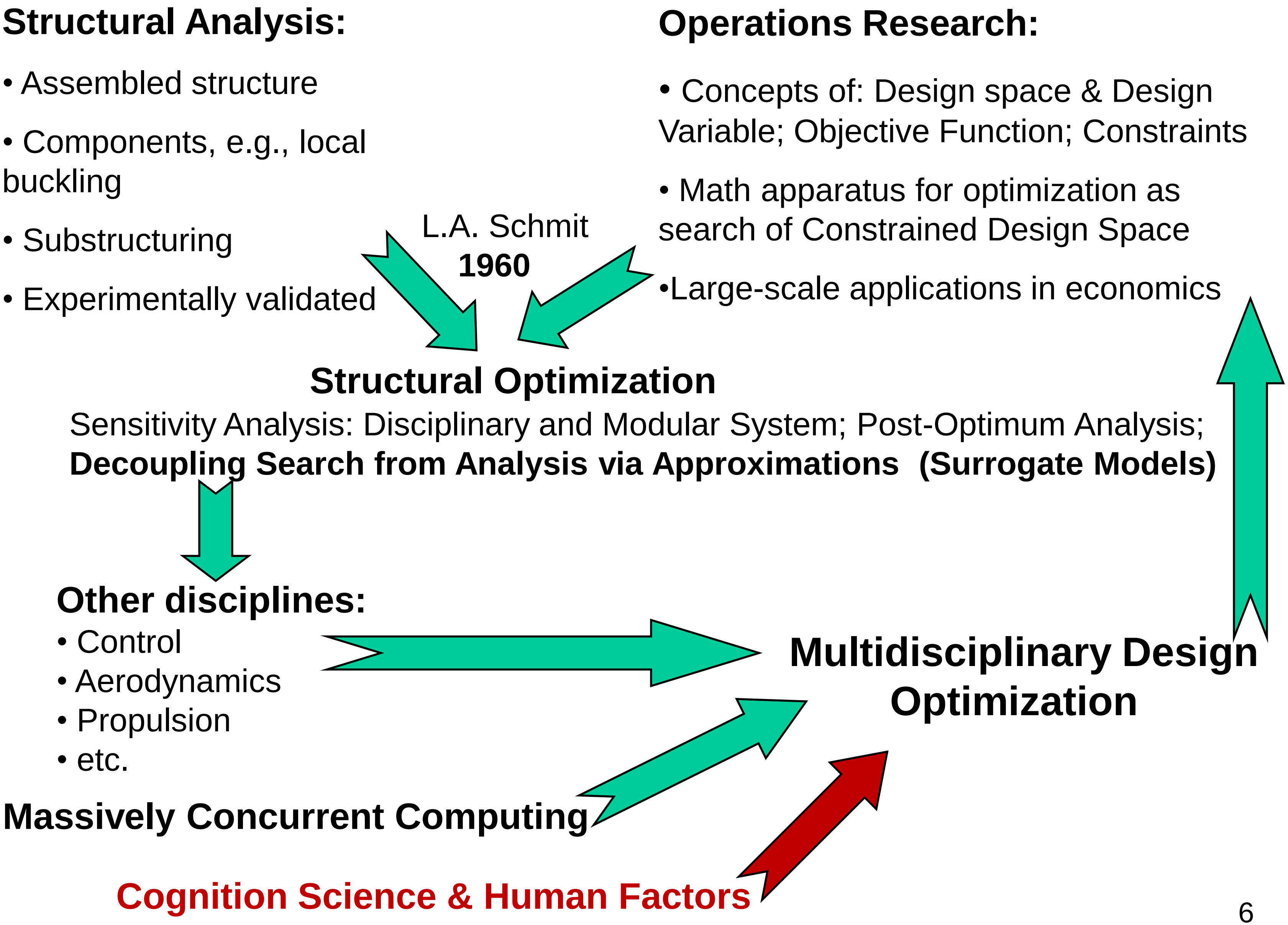
$\partial P / \partial t$

Optimizer

New t

Everything influences everything else

MDO Roots



Structural Analysis:

- Assembled structure
- Components, e.g., local buckling
- Substructuring
- Experimentally validated

Operations Research:

- Concepts of: Design space & Design Variable; Objective Function; Constraints
- Math apparatus for optimization as search of Constrained Design Space
- Large-scale applications in economics

L.A. Schmit
1960

Structural Optimization

Sensitivity Analysis: Disciplinary and Modular System; Post-Optimum Analysis; **Decoupling Search from Analysis via Approximations (Surrogate Models)**

Other disciplines:

- Control
- Aerodynamics
- Propulsion
- etc.

Massively Concurrent Computing

Cognition Science & Human Factors

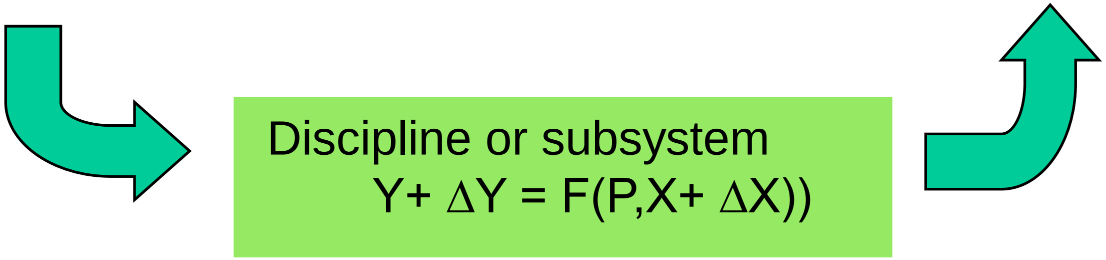
Multidisciplinary Design Optimization

Disciplinary analysis output change due to input change:
Sensitivity Analysis of $\boxed{F(Y,X) = 0}$

- Constant parameters **P**
- Design Variables X
- Increment ΔX

What If?

- State (behavior) variables Y
- Increment ΔY



Discipline or subsystem

$Y+ \Delta Y = F(P,X+ \Delta X))$

Tools Available

- Efficient Finite Difference techniques with error control

- Quasi-analytical sensitivity analysis based on Implicit Function Theorem

Set of linear equations $\Longrightarrow$ $[\partial F/\partial Y]\{\partial Y/\partial X_j\} = \{\partial F/\partial X_j\}$ extensible to higher order ∂/∂

- If the number of constraints g(X) is less than the number of design variables X, then it is cheaper to obtain $\partial g/\partial X_j$ by **Adjoint** version of the above equations

- **Automated Differentiation techniques**

- Derivatives via Imaginary Numbers

- **Search guided**
- **Engineering judgment inspired**

Sensitivity of Optimum to Problem Parameters

- **Example: TOGW has been minimized for a flight range R; sensitivity of TOGW to R?**
- Assume that an optimal solution X* has been obtained
  - the K-T conditions for optimality are satisfied.
- For some small change in problem parameter, we require that K-T conditions remain valid - differentiating these conditions wrt p (where p = R) one obtains

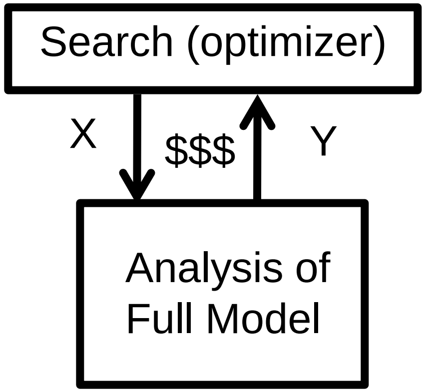
$$\partial \left(\begin{array}{l} \nabla f(X^*) + \sum_{j \in J} \lambda_j \nabla g_j(X^*) = 0 \\ g_j(X^*) = 0, \;\; \lambda_j > 0, \;\; j \in J \end{array} \right) / \partial \mathrm{p}$$

$$\begin{bmatrix} A_{nxn} & B_{nxJ} \\ B^T{}_{Jxn} & O_{JxJ} \end{bmatrix} \begin{Bmatrix} \delta X \\ \delta \lambda \end{Bmatrix} + \begin{Bmatrix} c_{nx1} \\ d_{Jx1} \end{Bmatrix} = 0$$

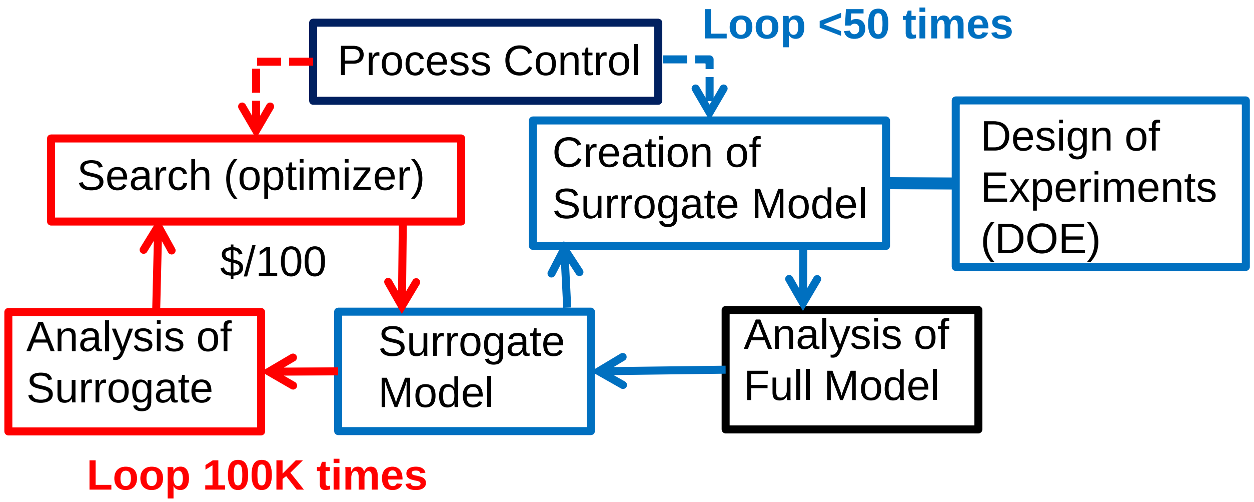
- abridged: **d f / d p = ∂ f / ∂ p + { λ }' ∂ { g$_c$ } / ∂ p**; **Caveat**: { **g$_c$** } must not change in the neighborhood of the point where d f / d p is evaluated.

Optimization Migrating from Structures to Other Disciplines

- Aerodynamics, Thermodynamics, Electromagnetic radiation, and more
- It became fundamental enabler in Composite materials
- It has always been the workhorse in space probe trajectory design
- Variety of techniques for decomposition of large problems into more manageable smaller ones have been developed
- **Search and Analysis decoupled via Approximations (Surrogate Models)**

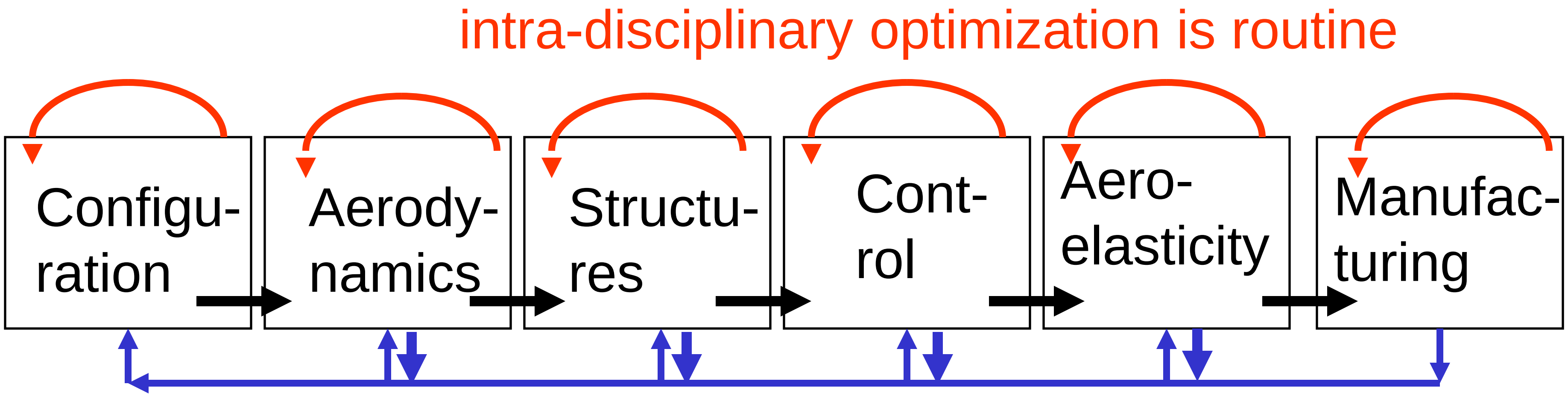


When model is inexpensive to analyze



Current practice in optimization applied to models expensive to analyze.

Sequential Design Process
Example: Aircraft


intra-disciplinary optimization is routine

Configu-ration

Aerody-namics

Structu-res

Cont-rol

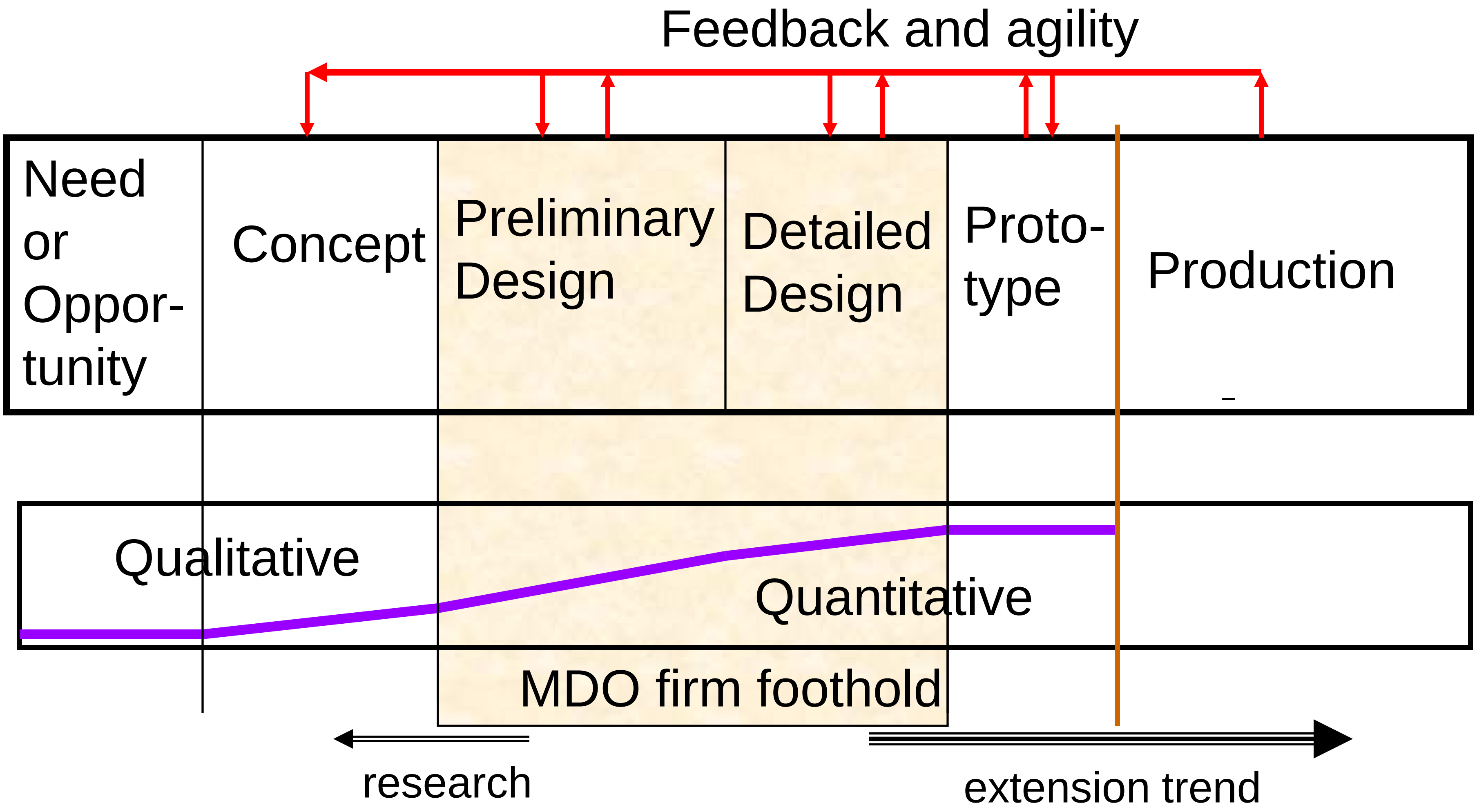
Aero-elasticity

Manufac-turing

interdisciplinary feedbacks and optimizations are discouraged by cost and time required to reopen decisions already made.

- MDO in Concurrent Engineering approach strives to make optimization and feedback routine, both intra- and inter-disciplinary.

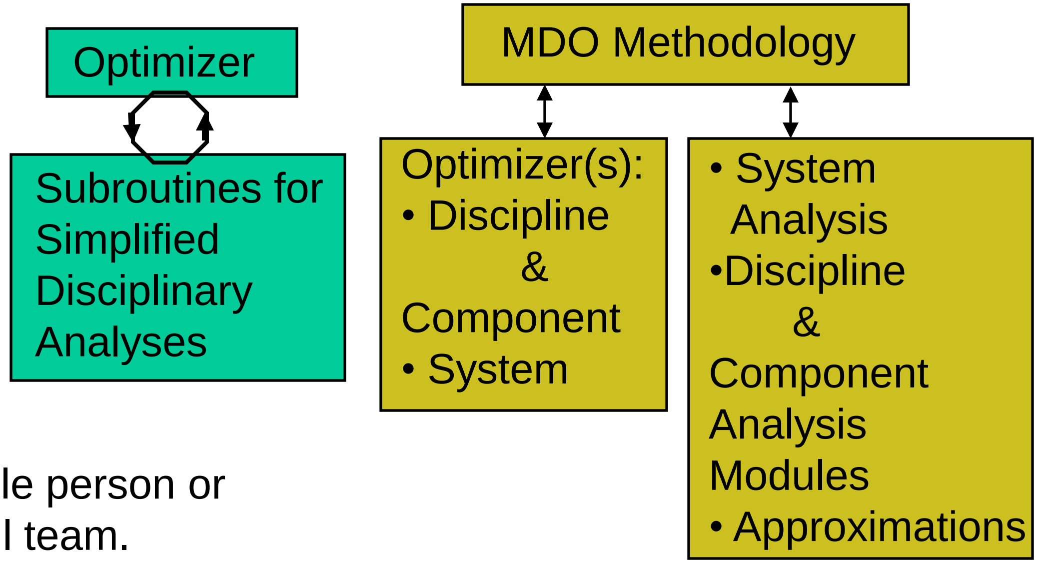
Optimization in Design Process



- Optimization most useful where quantitative content is high

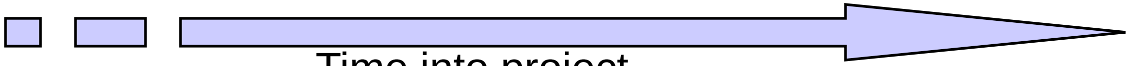
Optimization in Design Process

Need or Opportunity	Concept	Preliminary Design	Detailed Design	Prototype	Production

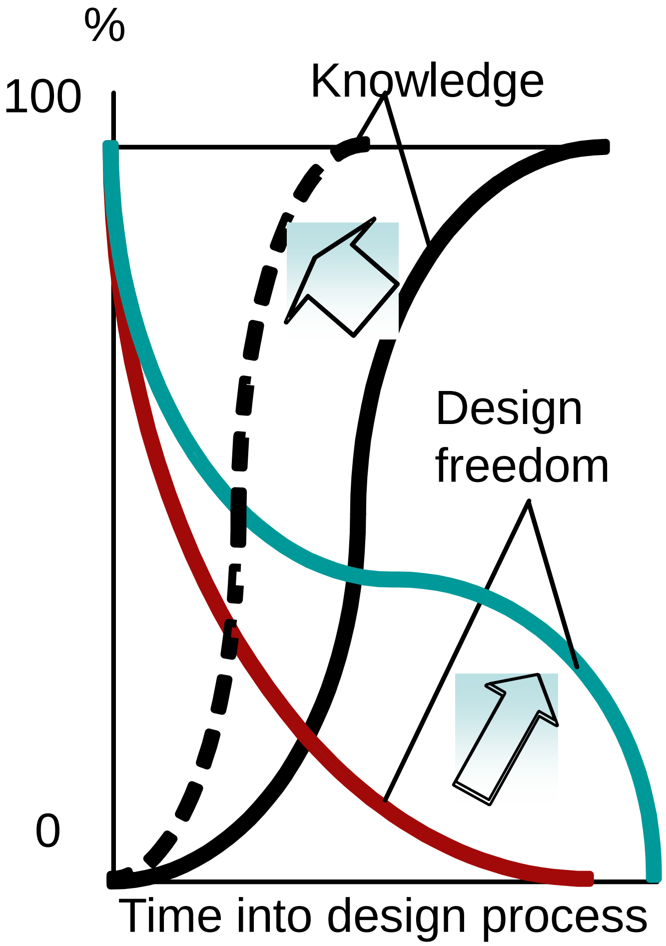


- Single person or small team.
- Optimizer calls on a single code invoking disciplinary subroutines.

- Depth of detail explodes volume of information and team size.
- Decomposition becomes necessity
- Concurrent operations, dispersal


Time into project

Sequential Design Process Paradox and MDO Remedy



- PARADOX:

As the design process advances,
the knowledge increases but the freedom
to act on that knowledge decreases.

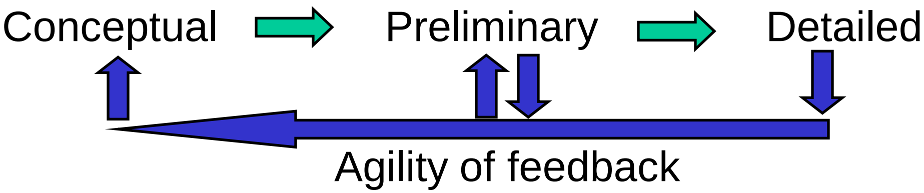
AXIOM:

If design A is one based on full knowledge,
and B is based on less than full knowledge,
then B is inferior to A.

MDO REMEDY:

Accelerate generation of knowledge
&
Retain more of design freedom longer

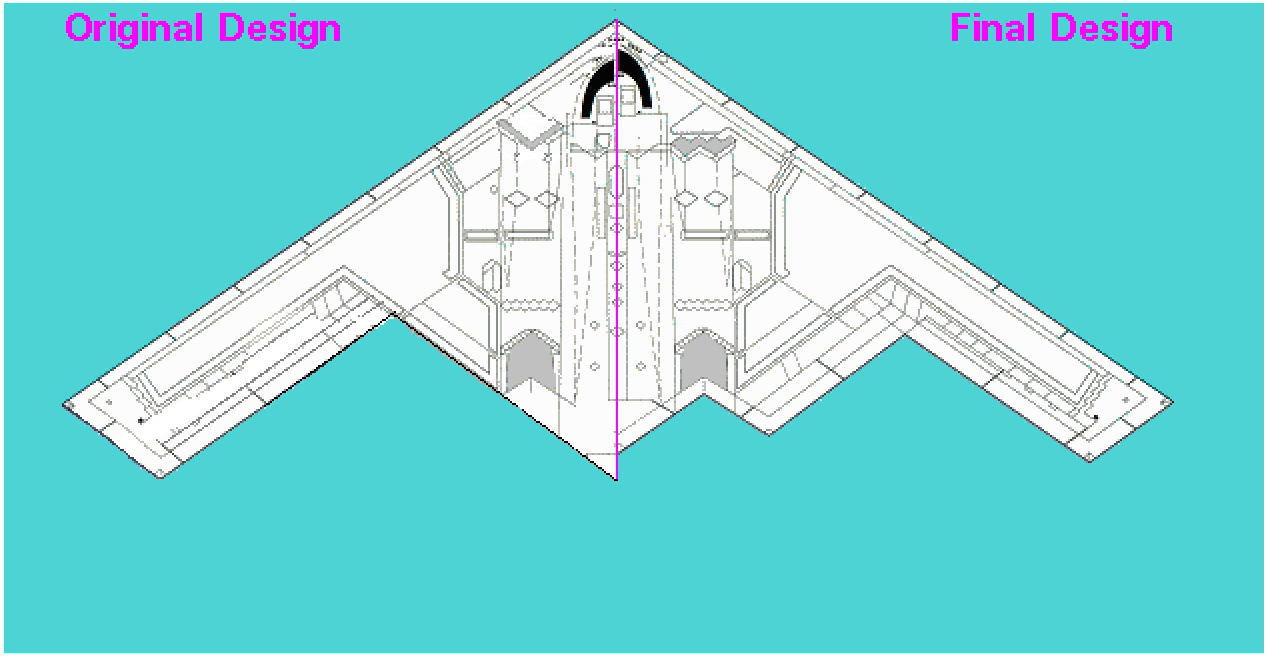
Design Process needs Agility and Capability to Handle Huge Volumes of Variables



Agility of feedback

- Agility: ability to act on new information uncovered downstream, even if it requires revisions at conceptual level

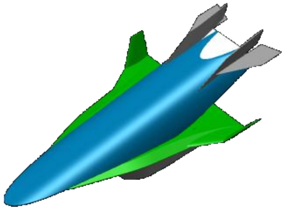
- MDO & Multiprocessor computing meets the challenge of agility



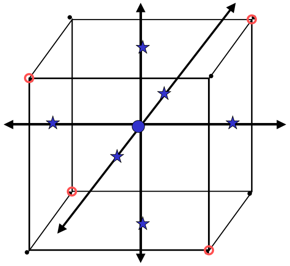
Boeing's Design Explorer Tool Suite Used to Perform Hypersonic Aircraft Configuration Optimization Using Approximations

Optimization Problem

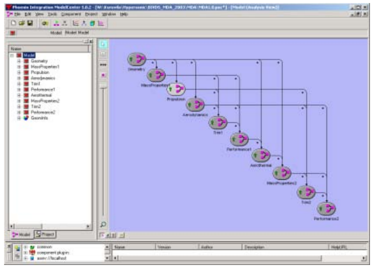
- **Find vehicle 2nd-stage shape parameter values that minimize TOGW**
- **Constraints: fixed payload, achieve orbit, maintain adequate thermal protection**



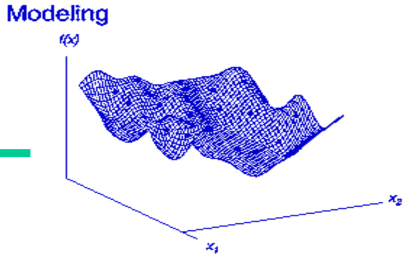
Develop Parametric Geometry Model & Select Optimization Parameters



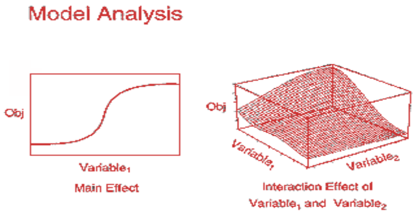
Construct Design of Experiments – Defines Vehicle Set for Analysis



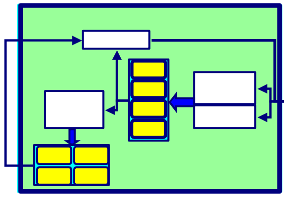
Perform Multidisciplinary Design Analysis of Vehicle Set



Create Response Surface Model of MDA Output (Kriging Model)



Analyze Model Quality (Analysis of Variance)

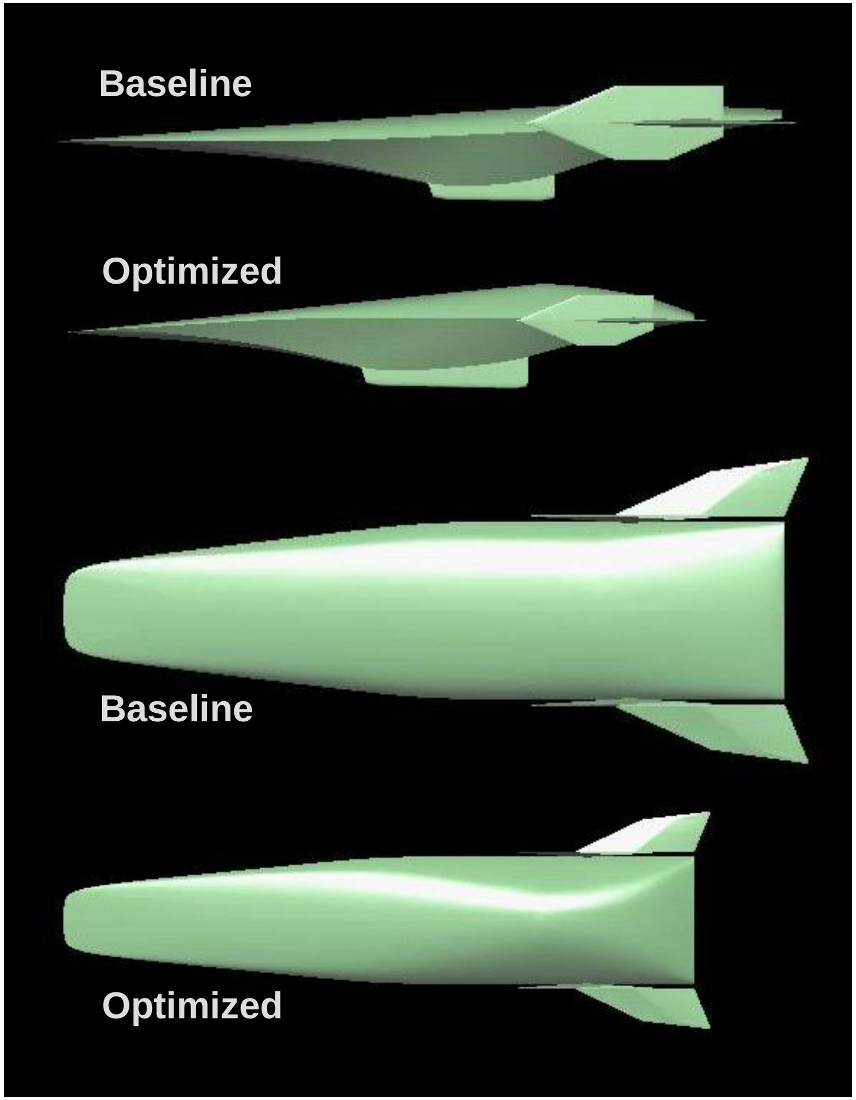


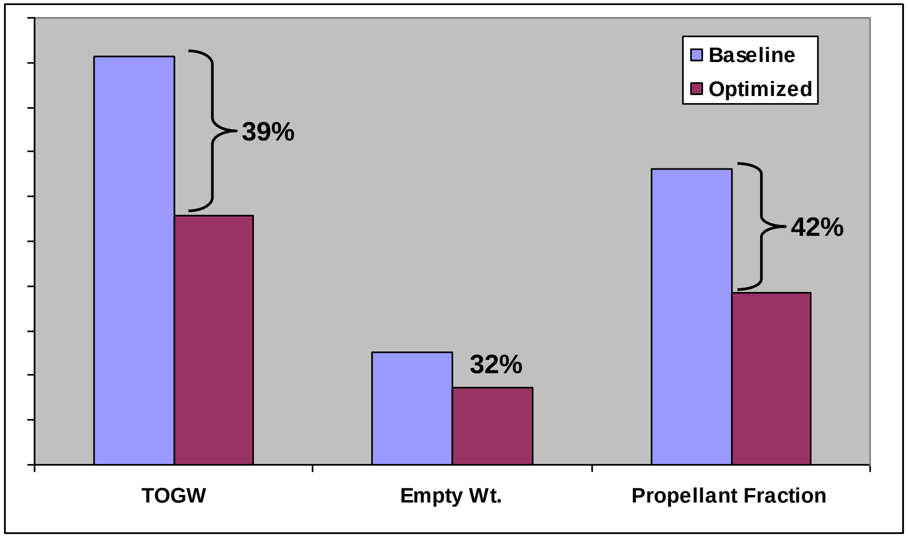
Run Optimizer

Add Configuration Design Details

Refine Optimization

Dramatic Benefits and Tradeoffs Apparent in MDO Results

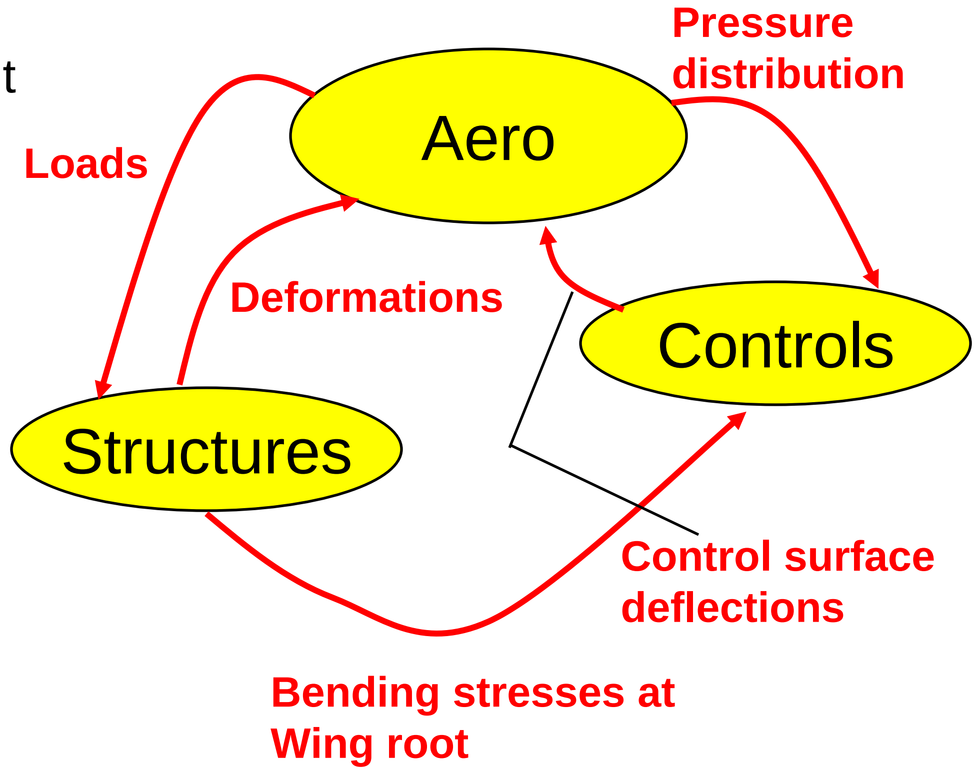




- MDO as a way to make design task manageable
    - System sensitivity
    - Organization of Information
    - Decomposition: Bi-Level Integrated System Synthesis (BLISS)

Design Problems in which Disciplines Interact

- This system is not hierarchial
- All disciplines equally important



Pressure distribution

Aero

Loads

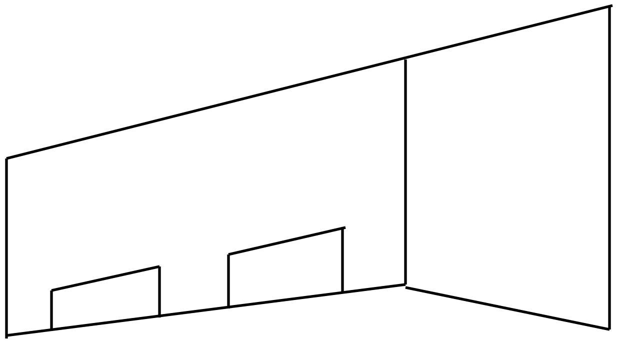
Deformations

Controls

Structures

Control surface deflections

Bending stresses at Wing root

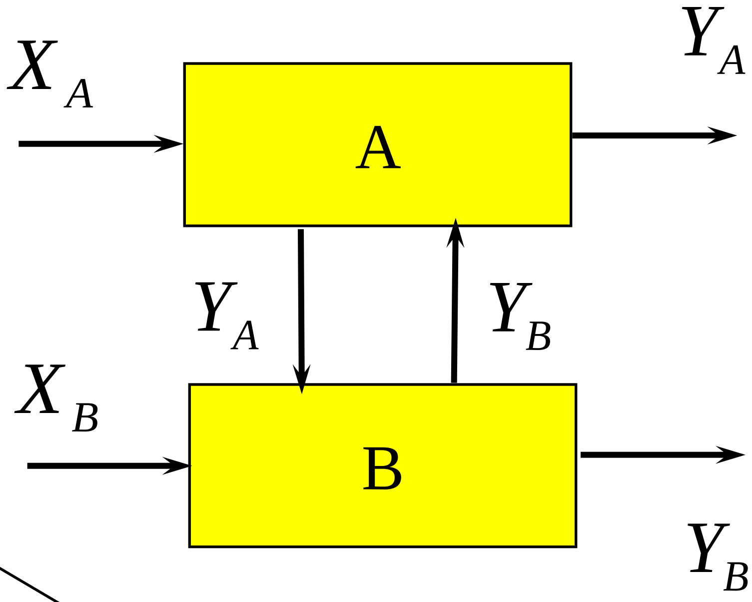


- Aircraft wing as example of an engineering system: "An entity of subsystems and physical phenomena, all interacting with each other, whose design engages many disciplines and specialties".

EVERYTHING INFLUENCES EVERYTHING ELSE

Coupled System Sensitivity - 1

- Consider a multidisciplinary system with two subsystems A and B
  - system equations can be written in symbolic form as
  - rewrite these as follows



$$A[(X_A, Y_B), Y_A] = 0$$
$$B[(X_B, Y_A), Y_B] = 0$$

$$Y_A = Y_A(X_A, Y_B)$$
$$Y_B = Y_B(X_B, Y_A)$$

these governing equations define

as implicit functions.
Implicit Function Theorem applies.

Coupled System Sensitivity - 2

- These equations can be represented in matrix notation as

- Total derivatives can be computed if partial sensitivities computed in each subsystem are known - the latter can be computed locally within the subsystems

$$\begin{bmatrix} I & -\dfrac{\partial Y_A}{\partial Y_B} \\ -\dfrac{\partial Y_B}{\partial Y_A} & I \end{bmatrix} \begin{Bmatrix} \dfrac{dY_A}{dX_A} \\ \dfrac{dY_B}{dX_A} \end{Bmatrix} = \begin{Bmatrix} \dfrac{\partial Y_A}{\partial X_A} \\ 0 \end{Bmatrix}$$

$$\begin{bmatrix} I & -\dfrac{\partial Y_A}{\partial Y_B} \\ -\dfrac{\partial Y_B}{\partial Y_A} & I \end{bmatrix} \begin{Bmatrix} \dfrac{dY_A}{dX_B} \\ \dfrac{dY_B}{dX_B} \end{Bmatrix} = \begin{Bmatrix} 0 \\ \dfrac{\partial Y_B}{\partial X_B} \end{Bmatrix}$$

same matrix

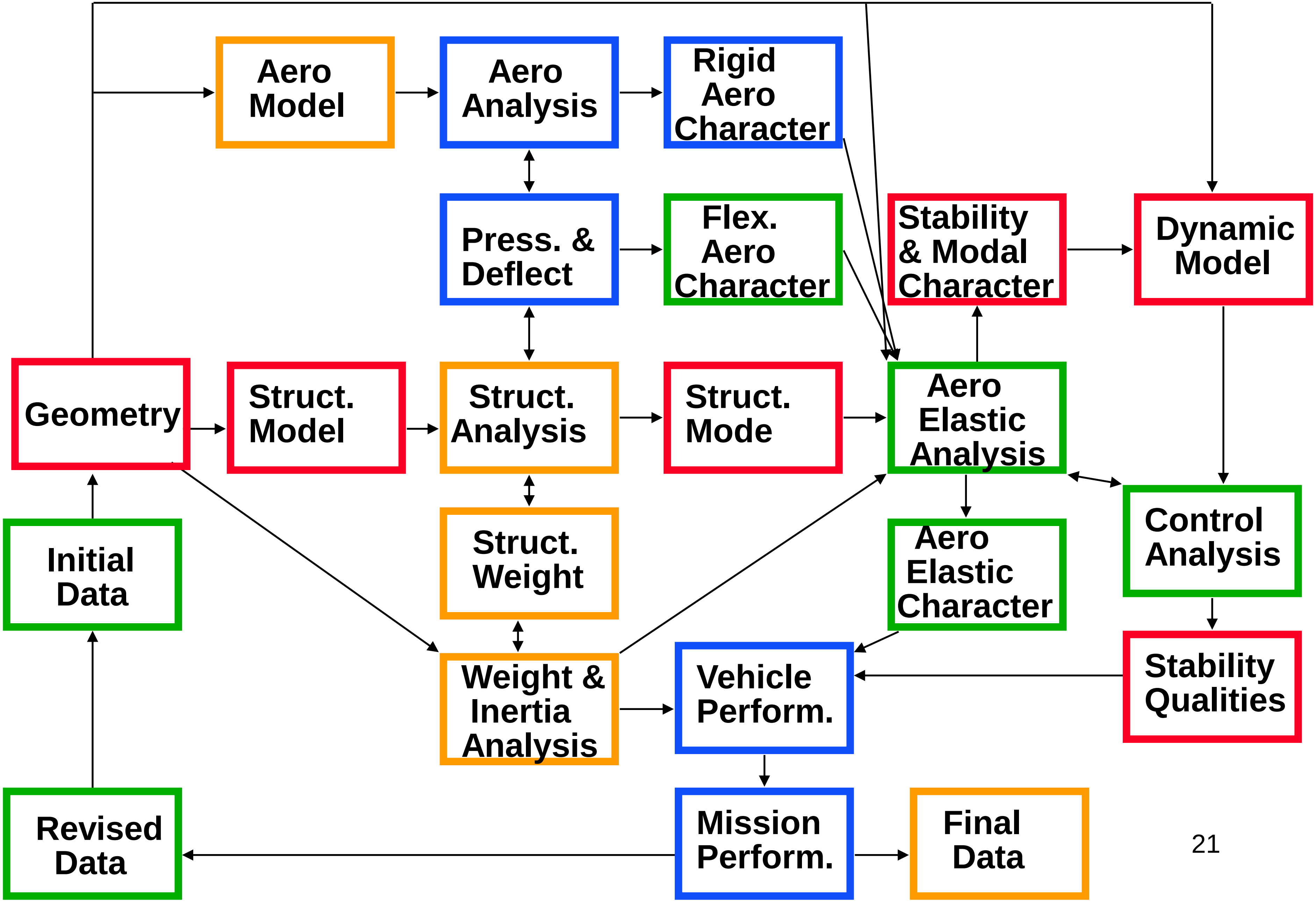
different Right Hand Sides

Linear, algebraic equations with multiple RHS

- Factor matrix once, F-B Substitute multiple RHS, one per X_i

As Problems Become Large Data Handling Becomes Very Important

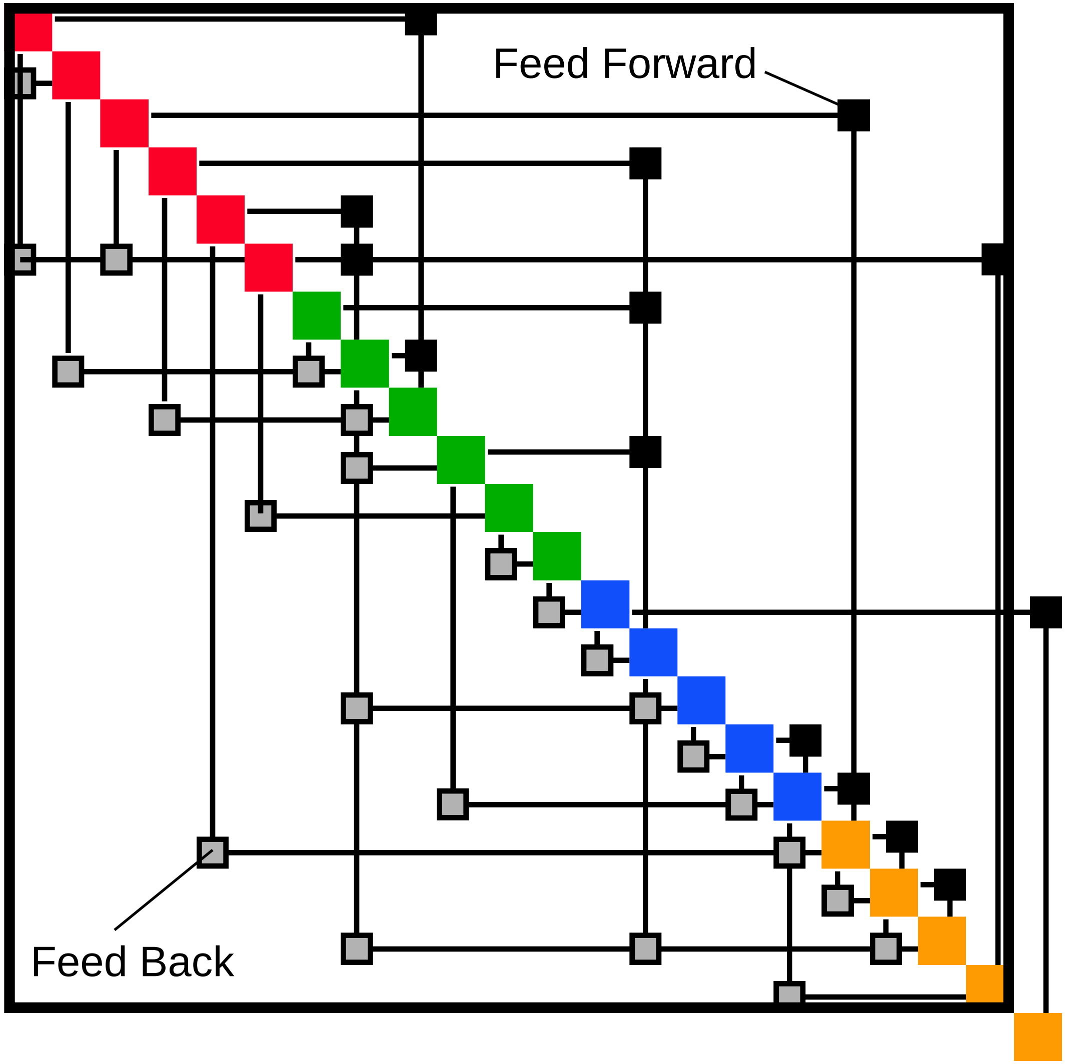
Example: Aircraft Design Process



Aircraft Computational Operations and Data as N-square Diagram (a.k.a. Design Dependency Matrix, DDM)

Process	Time	Cost
DYNMODL	30	30
STDMOCH	40	20
STRMODL	10	50
HANDQUL	10	50
STRMODE	10	50
GEOMDEV	50	10
AROSRVO	40	20
STRDYNA	50	10
CSVSANL	20	40
FAEROCH	20	40
INITDAT	40	20
RVSEDAT	30	30
MISPERF	30	30
VEHPERF	20	40
RAEROCH	30	30
AEROANL	20	40
PRESDEF	30	30
STRANAL	40	20
STRCTWT	50	10
WIANAL	40	20
AEROMDL	20	40
FINLDAT	20	40

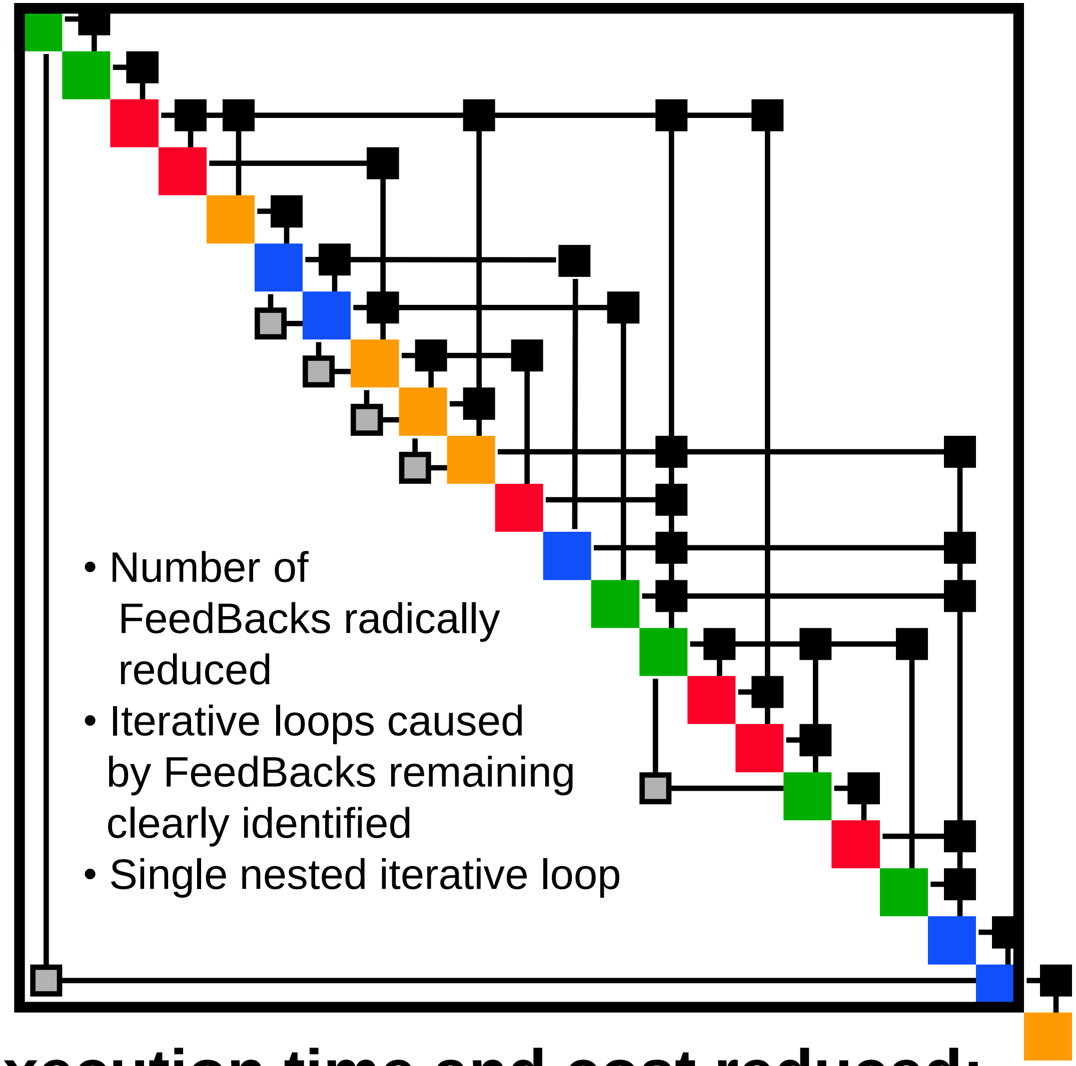
Space Shuttle Orbiter



Execution: Time - 21,340 **Cost - 19,640**

Reduced Design Cycle Time and Cost by Permuting DDM Rows & Columns: Space Shuttle Application

Process	Time	Cost
RVSEDAT	30	30
INITDAT	40	20
GEOMDEV	50	10
STRMODL	10	50
AEROMDL	20	40
AEROANL	20	40
PRESDEF	30	30
STRANAL	40	20
STRCTWT	50	10
WIANAL	40	20
STRMODE	10	50
RAEROCH	30	30
FAEROCH	20	40
STRDYNA	50	10
STDMOCH	40	20
DYNMODL	30	30
CSVSANL	20	40
HANDQUL	10	50
AROSRVO	40	20
VEHPERF	20	40
MISPERF	30	30
FINLDAT	20	40



- Number of FeedBacks radically reduced
- Iterative loops caused by FeedBacks remaining clearly identified
- Single nested iterative loop

- **Execution time and cost reduced:**

Time from 21,340 to 3,800 Cost from 19,640 to 3,220

Realities of Engineering Team Work Must Be Respected

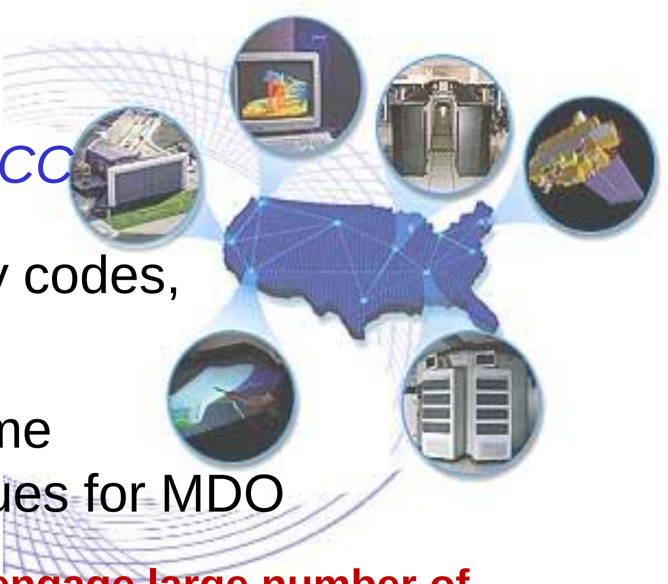
- Engineers form groups aligned with project components: disciplines, parts, and processes
- Groups have authority to decide within their domains, not only to analyze
- Groups own their methods and tools
- Engineers exercise judgment, individual and collective using ALL available information
- Groups control their work schedules within team deadlines
- Groups may be geographically dispersed
- Groups collaborate toward the system objectives.
- Concurrent operations compress the project elapsed time

Any MDO method to support an Engineering Team must comply with all of the above

Massively Concurrent Computing (MCC)

- Many processors in one box
- Multitude of single processor computers clustered (e.g., 10,000 cluster of Apple G5 at Virginia Tech)
- Multitude of processors in one installation (> 100,000 available now at Livermore Lab (IBM), 1 million expected soon)
- Field-programmable Gate Array computers – reconfigurable to N processors.
- Variety of processor-local memory – shared memory – mass storage

offer diverse computer architectures.



Continent-spanning networks support MCC

- **Coarse-grained parallelism** now using legacy codes, next: new codes **re-written from scratch**.
- Potential for **10^6 to 10^7** reduction of elapsed time for complex math model analysis = new avenues for MDO
- **New metric of merit for numerical methods: Ability to engage large number of concurrently operating processors for compression of the task elapsed time.**

Commercial Toolboxes Emerged

- Popular packages bring optimization to millions of users
  - EXCEL, MATLAB Optimization ToolBox, Mathematica

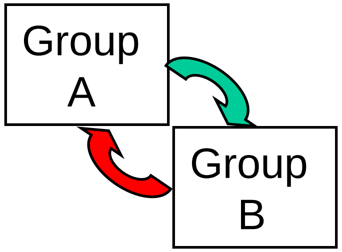
- Vendors offer integration and optimization tools to engineering corporations
  - Altair
  - Engineous
  - Vanderplaats R & D: Genesis/DOT
  - Boeing: Design Explorer

  - **Integrated Concurrent Engineering ICE**
    - **Application at MIT to be visited later**
  - **Phoenix: ModelCenter/CenterLink/Bi-Level Integrated System Synthesis (BLISS)**
    - **Next charts introduce BLISS inner workings**

MDO challenge: How to break out of the Sequential Design Paradigm to achieve concurrency and specialist autonomy

- Groups A & B need input data from each other

Hence, “natural” process is **sequentially** iterative:

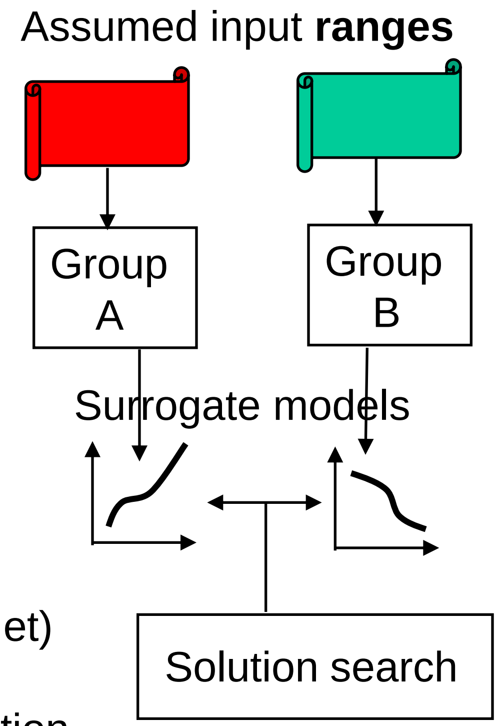


- “A” guesses on input from “B”
- “A” executes; passes output to “B”
- “B” executes; passes feedback output to “A”
- “A” re-executes to accommodate new data from “B”
- ….continue until converged

•Availability of massively concurrent computing technology enables new organization of the above process

Very simple concept:

- “A” assumes range of input from “B”, “B” *ditto* from “A”
- “A” and “B” work concurrently to generate their outputs
  - each does this in the space of its input at DOE-generated points
  - each fits a surrogate model (Response Surface, kriging, Neural Net) to represent its **output = f(input)**
- Search algorithm (optimizer) uses surrogate models to find A & B solution



•Result: **sequentially** iterative process converted to **concurrently** iterative

- Bulk of computing effort accomplished simultaneously; **elapsed time compressed**
- **Groups remain autonomous in their modes of operandi and choice of tools**

System Optimization Dilemma

- If they are to optimize concurrently and to remain coupled by data exchange, then

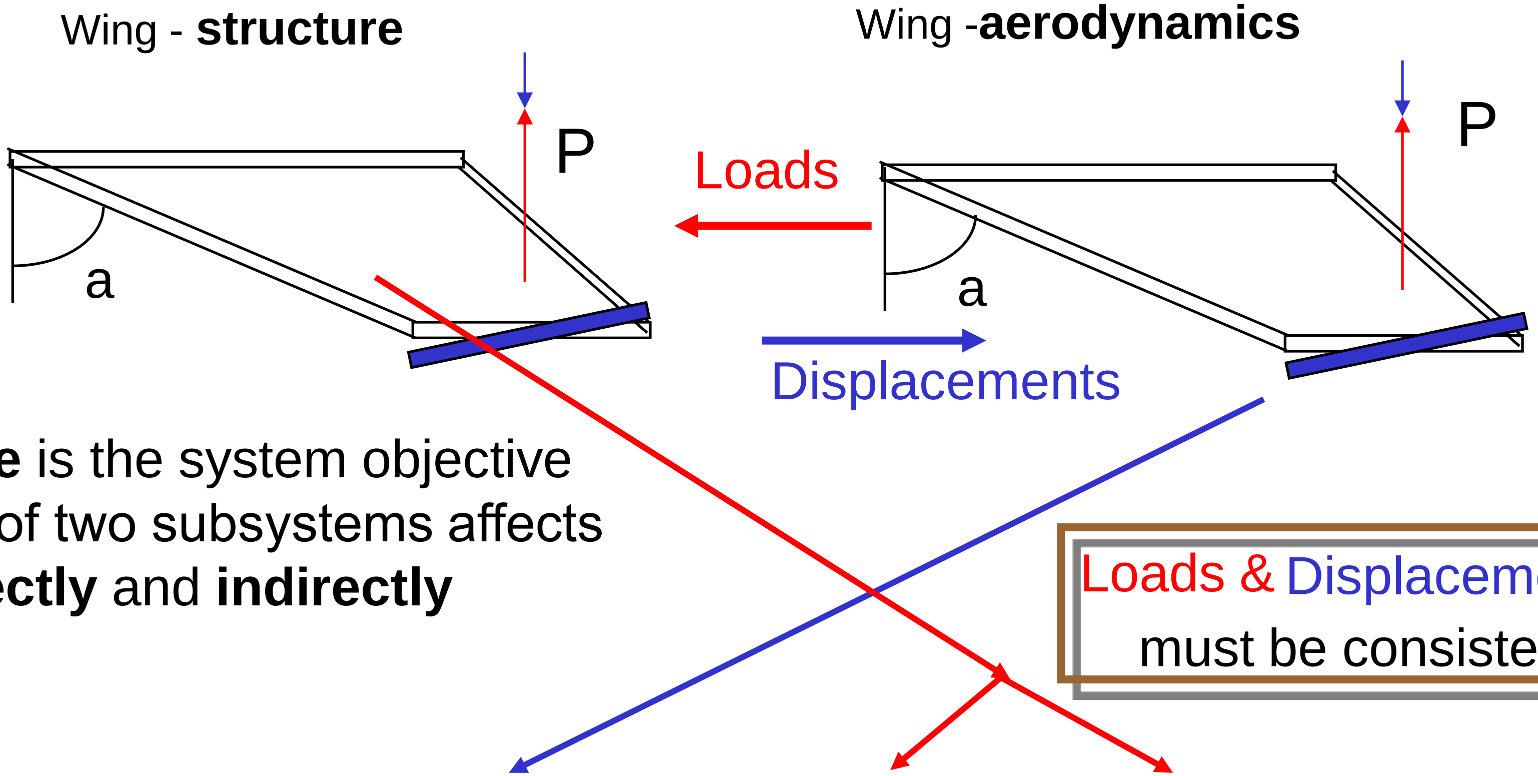
A basic question arises:

What objectives should each group optimize for?

- Several MDO methods offer answer to the above question – see Supplemental Reading at the end.

Bi-Level Integrated System Synthesis, BLISS, is one answer – following charts

Example: Wing as System of Two Subsystems: Structures & Aerodynamics



- **Range** is the system objective
- Each of two subsystems affects **R directly** and **indirectly**

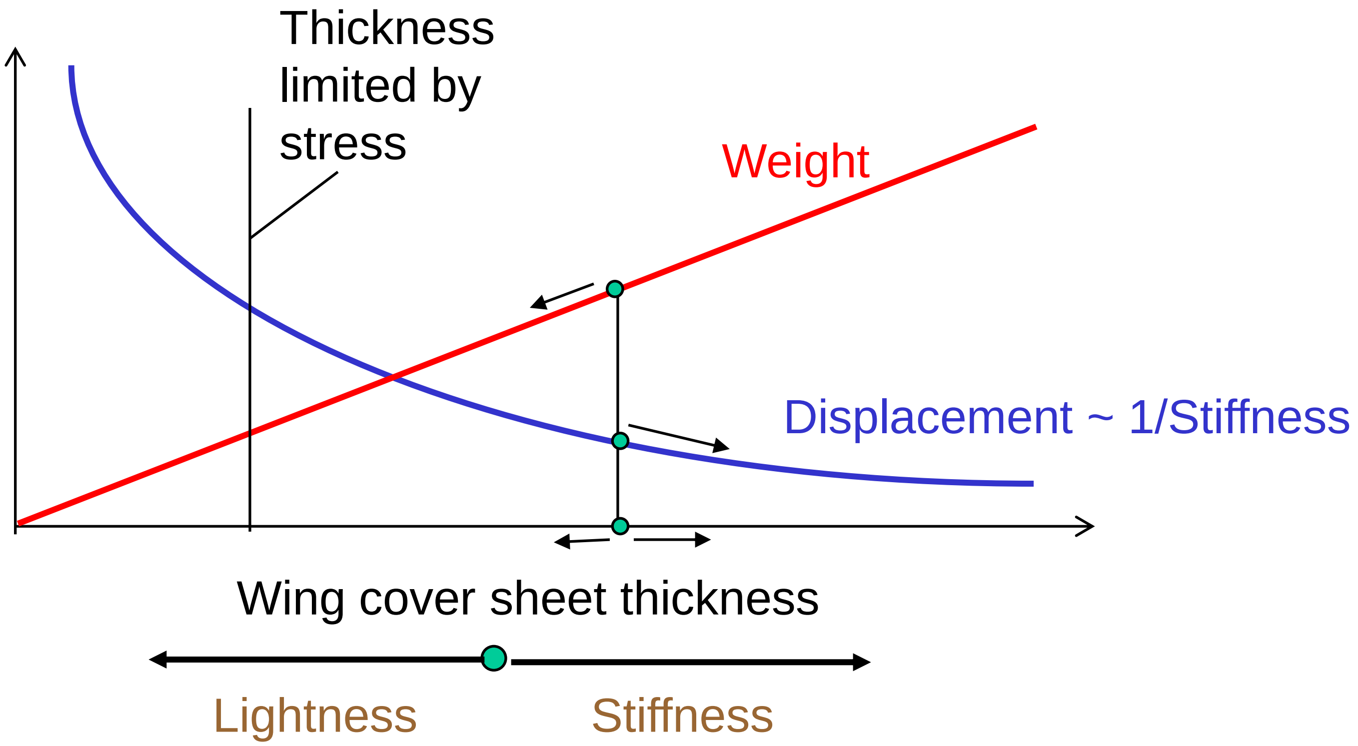
Loads & Displacements must be consistent

Range: $R = (c/Drag)\ LOG\ [(W_o + W_s + W_f)/ (W_o + W_s)]$

Eg.: Structures: **Directly** by w, **Indirectly** by Displacement → Drag

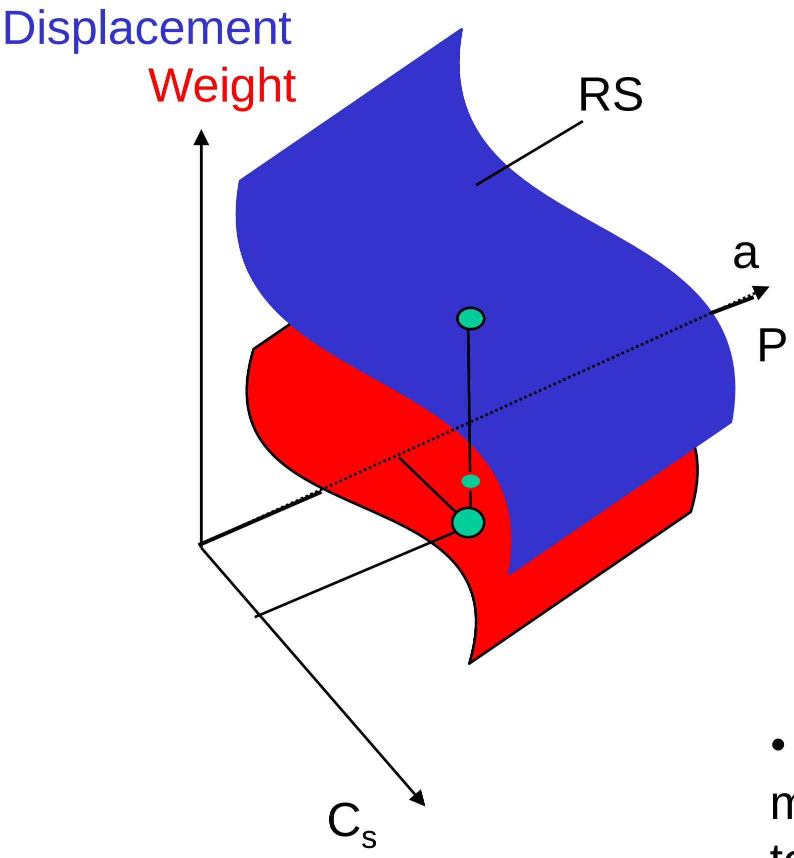
- **What to optimize the structure for? Lightness? Displacements = 1/Stiffness? An optimal mix of the two?**

Trade-off between opposing objectives of lightness and stiffness



- What to optimize for?
- BLISS Answer: minimum of $f = c_s1$ Weight $+ c_s2$ Displacement
- the weighting coefficients c_s1, c_s2 are, as yet, unknown.

Response Surface as Approximation of Structure Optimized locally



GIVEN: geometry “a”, load P,
and “c_s”

FIND: cross-sectional gages

MINIMIZE:
f = c_s1 Weight + c_s2 Displacement

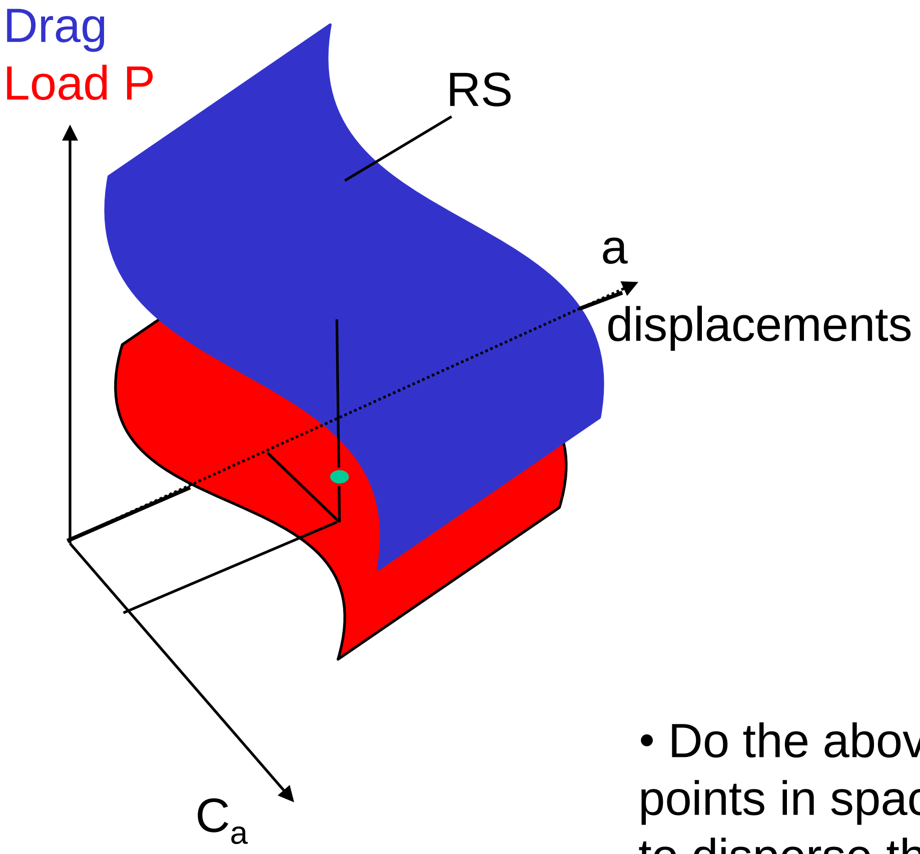
SATISFY: local constraints,
e.g., stress < allowed

- Do the above optimization (any technique) at many points in space (a, P, c_s); use DOE to disperse the points.

- Fit RS(weight) & RS(displacements)

- Save the RS for the system optimization

Response Surface as Approximation of Aerodynamics Optimized locally



GIVEN: geometry “a”,
displacements, and “c_a”

FIND: airfoil leading edge radius

MINIMIZE:
$f = c_a1$ Load $+ c_a2$ Drag

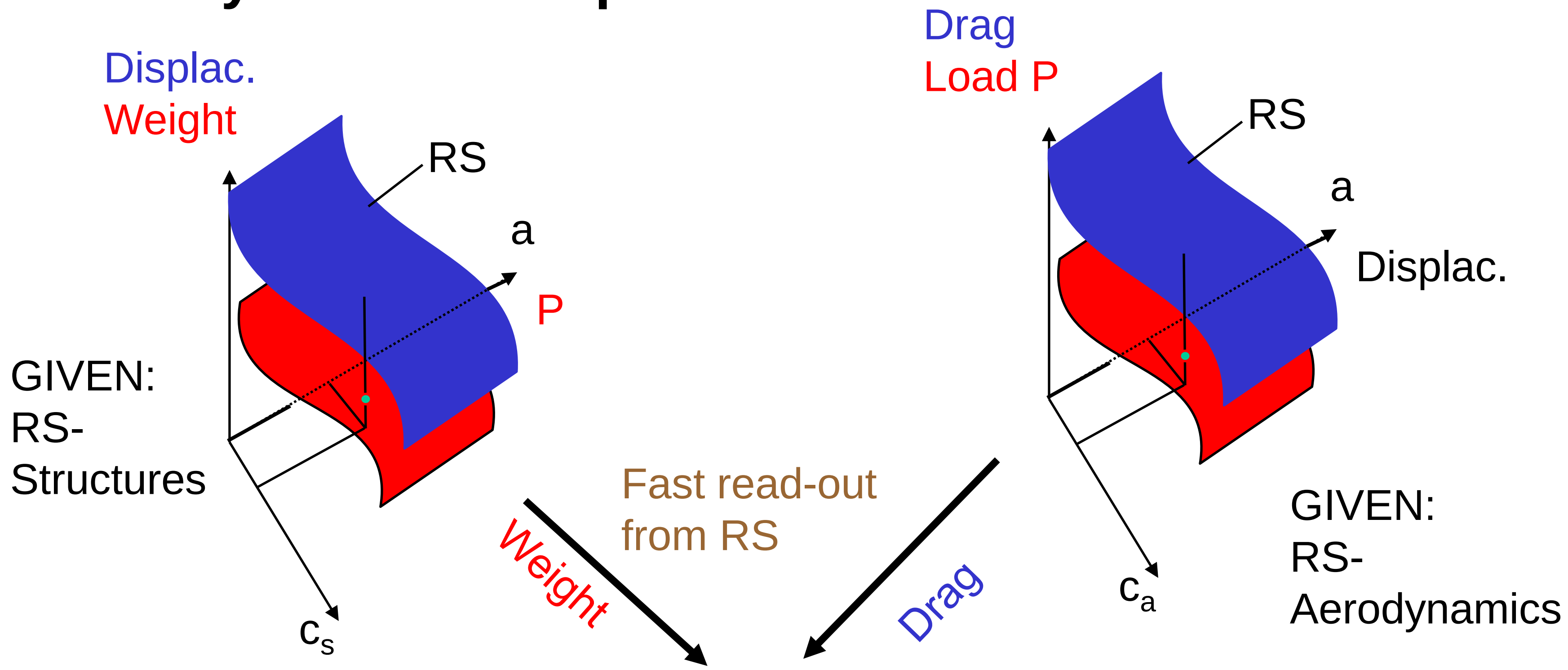
SATISFY: local constraints,
load = lift required

- Do the above optimization (any technique) at many points in space (a, P, c_a); use DOE to disperse the points.

- Fit RS(Load) & RS(Drag)

- Save the RS for the system optimization

System-level Optimization



System
optimizer
does this

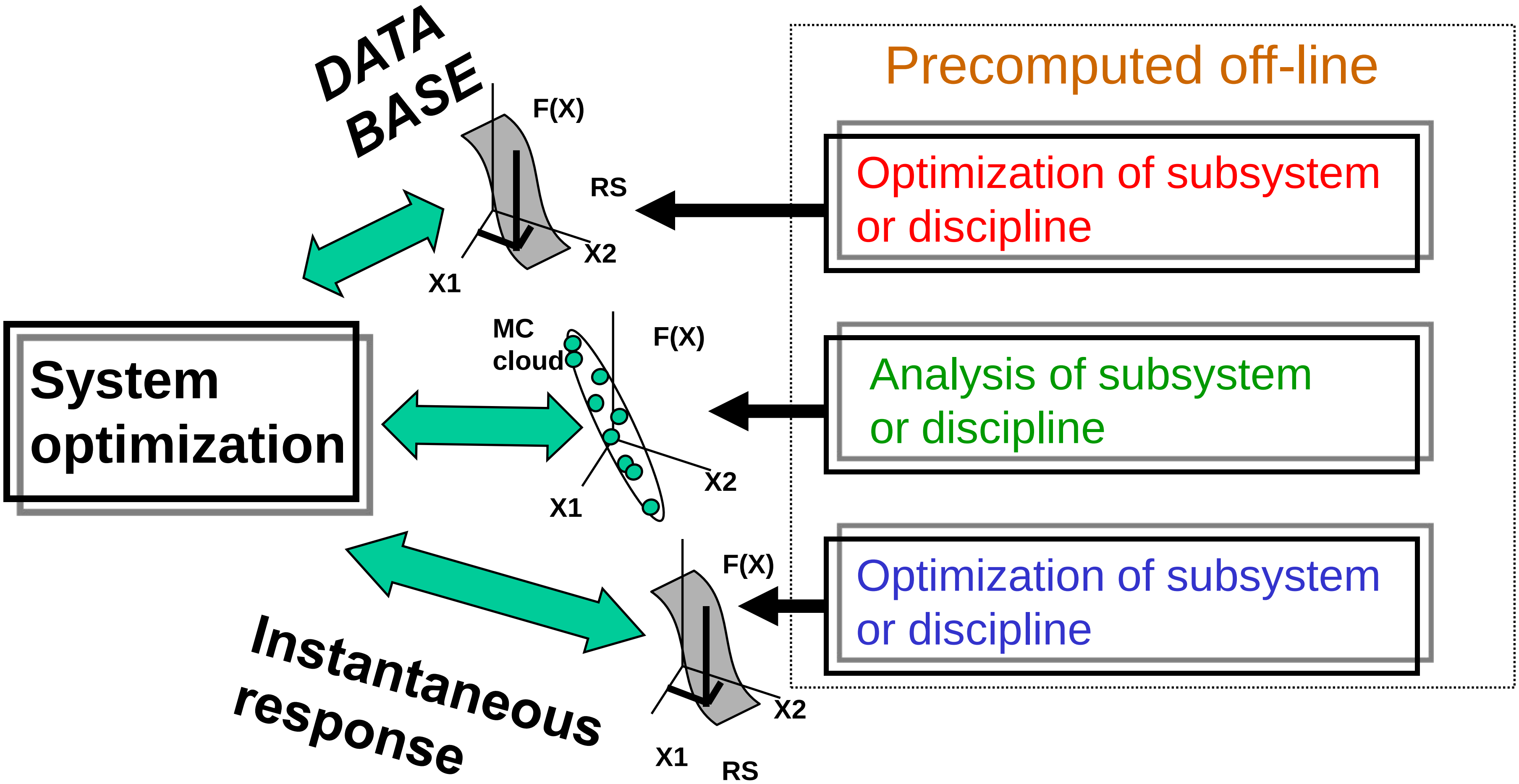
FIND: geometry “a”, P, Displacements, c_a, c_s

MAXIMIZE: $R = (c/\text{Drag})\ \text{LOG}\ [(W_o + W_s + W_f)/ (W_o + W_s)]$

SATISFY: P(a, Displac.) = Displac.(a, P)

- **This is the essence of Bi-Level Integrated System Synthesis, BLISS**

MDO Huge Computational Problem Solved by Decomposition, RS & Massively Concurrent Computing



System optimization

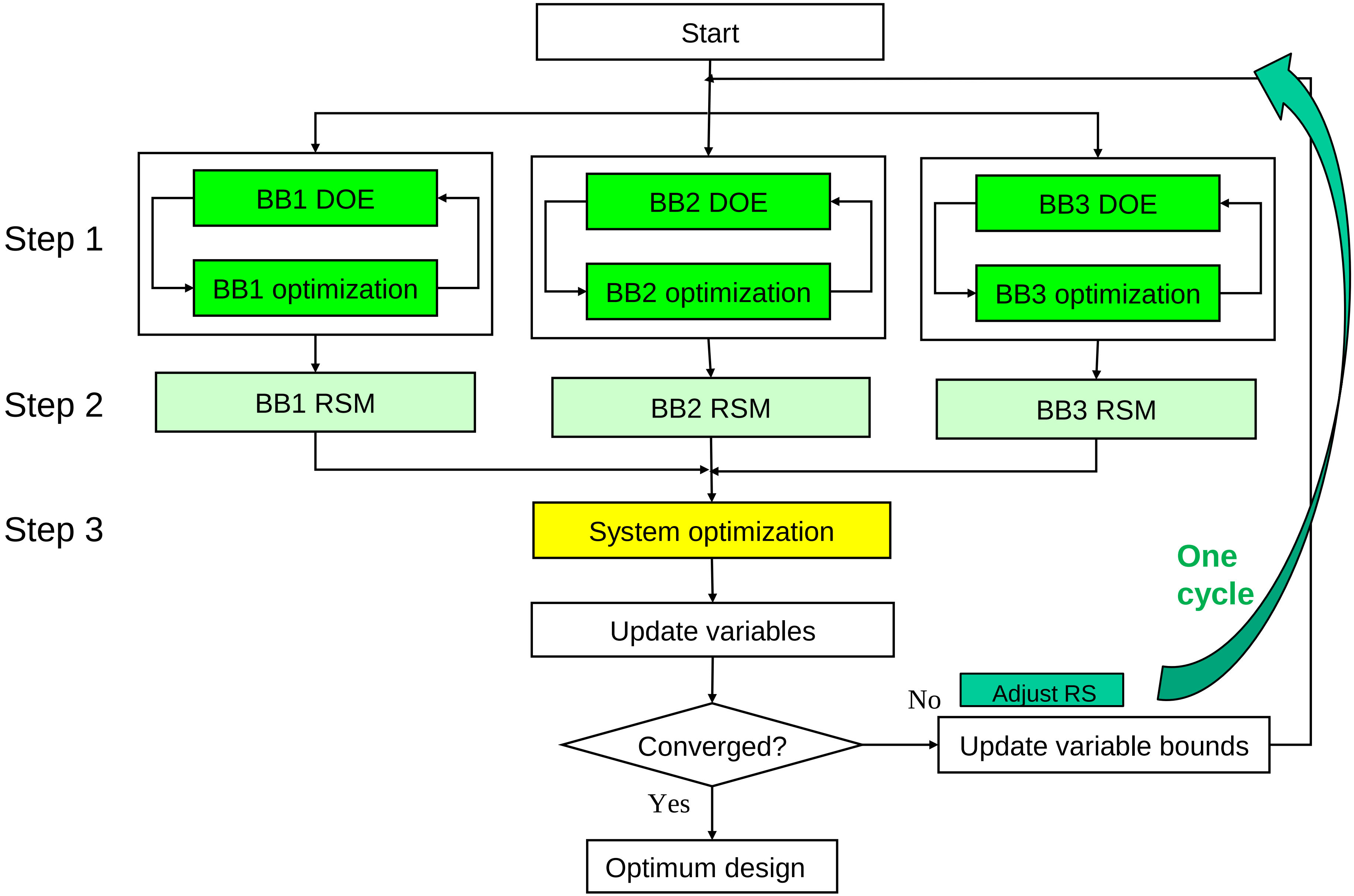
Precomputed off-line

Optimization of subsystem or discipline

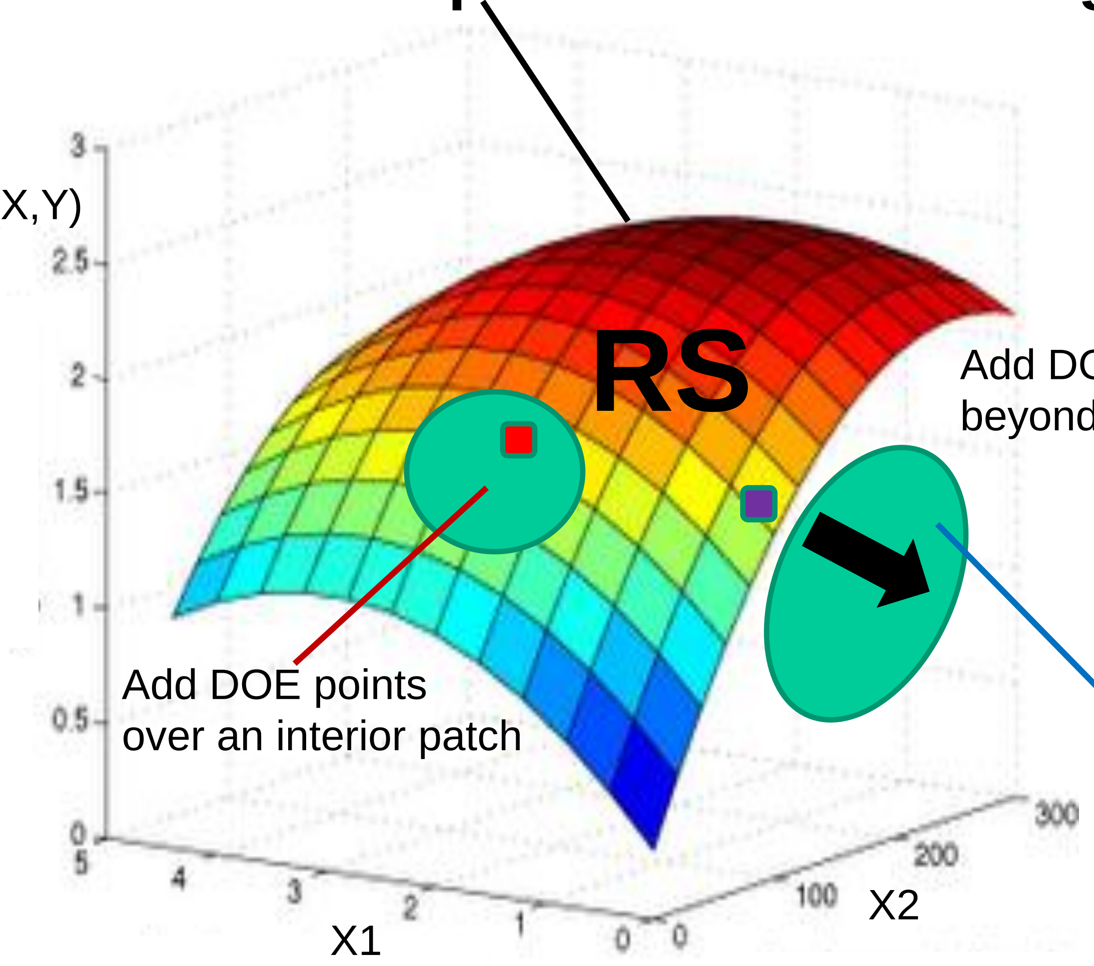
Analysis of subsystem or discipline

Optimization of subsystem or discipline

- **Simple concept at the price of a lot computing**
- **Taking advantage of computing getting cheaper, while labor getting dearer**


Start
Step 1
BB1 DOE
BB1 optimization
BB2 DOE
BB2 optimization
BB3 DOE
BB3 optimization
Step 2
BB1 RSM
BB2 RSM
BB3 RSM
Step 3
System optimization
Update variables
Converged?
Yes
No
Adjust RS
Update variable bounds
One cycle
Optimum design

Adjustments to Response Surface Surrogate Model



Add DOE points over a patch beyond the boundary

Add DOE points over an interior patch

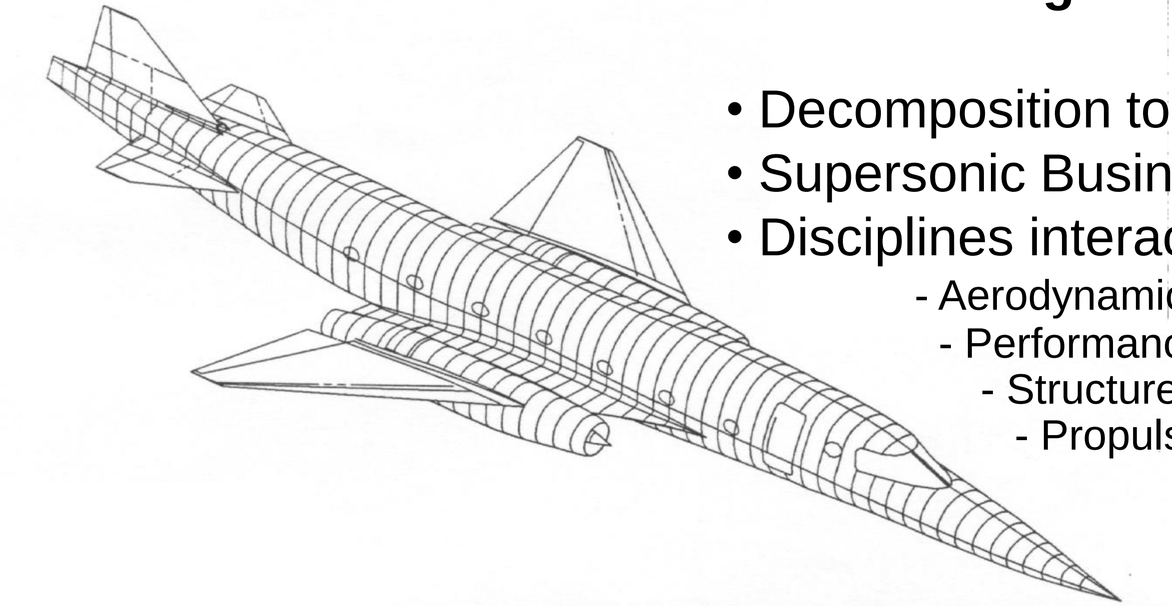
System Optimization ends at a point near RS boundary:

🟪 **add DOE points beyond the boundary to stretch RS**

🟥 System Optimization ends at a point within RS boundary: **add DOE points around the point**

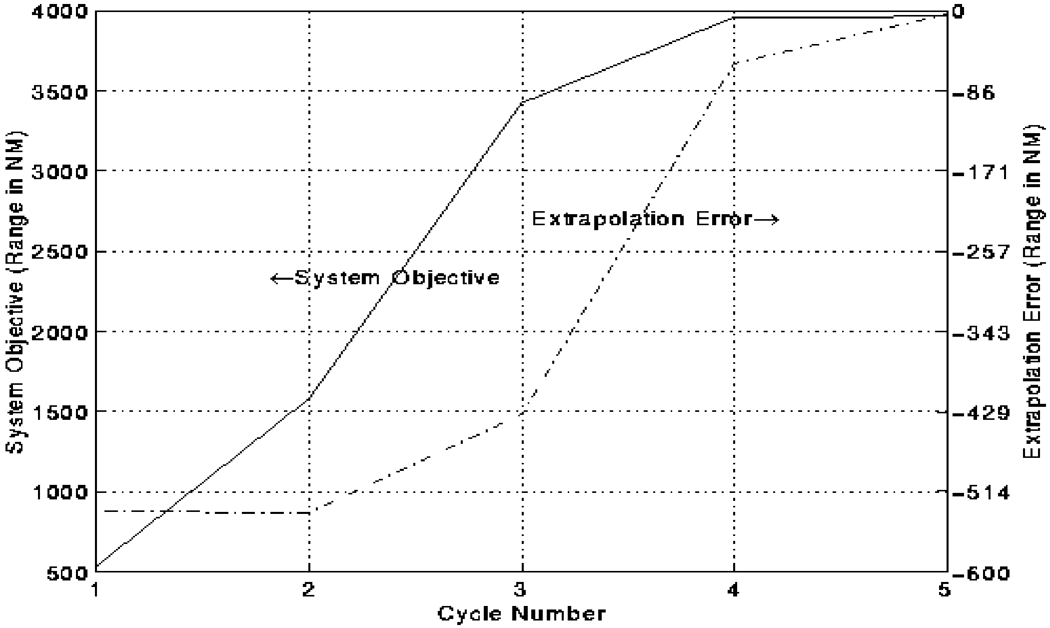
- MDO Assessment
  - Can do now well
  - Capabilities deficient, as yet
  - Avenues of development

Bi-Level Integrated System Synthesis (BLISS):



- Decomposition to simulate human organization
- Supersonic Business Jet Test case
- Disciplines interacting:
  - Aerodynamics
  - Performance
  - Structures
  - Propulsion

Objective: Max Range

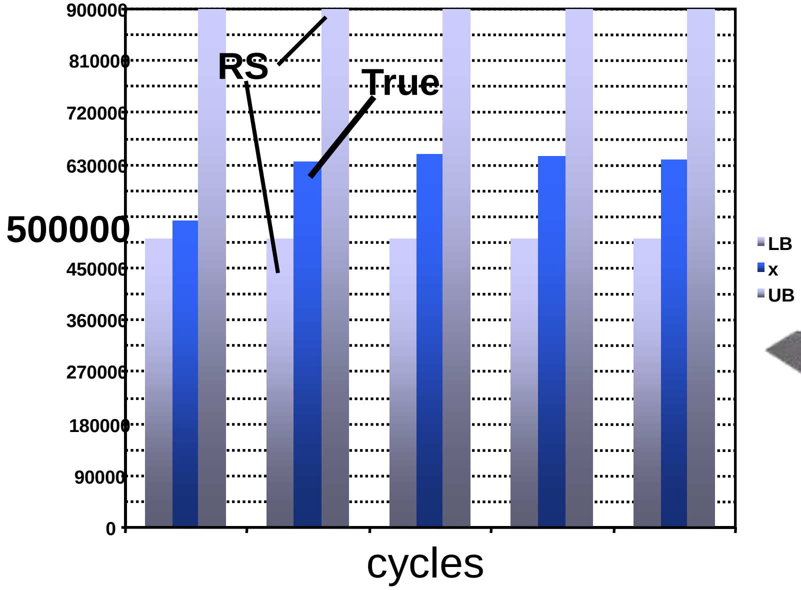


- Award:

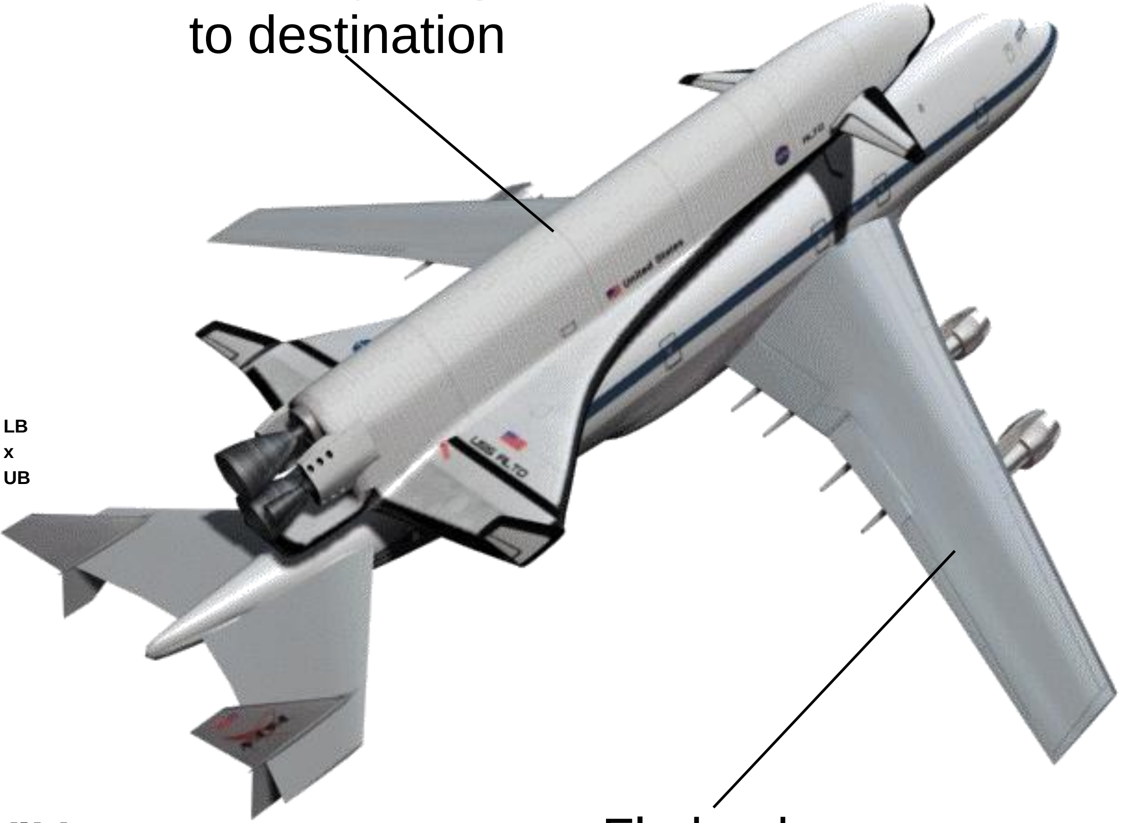
Society of Automotive Engineers (SAE) Wright Brothers Medal for 1999 @ World Aviation Congress 2000.

- BLISS was commercialized in 2005 in ModelCenter/CenterLink

Recent BLISS Application: Two-stage Orbital Transport



- **Result sample: System Weight (lb) Variance over BLISS iterations**.
- **Initial design was infeasible**

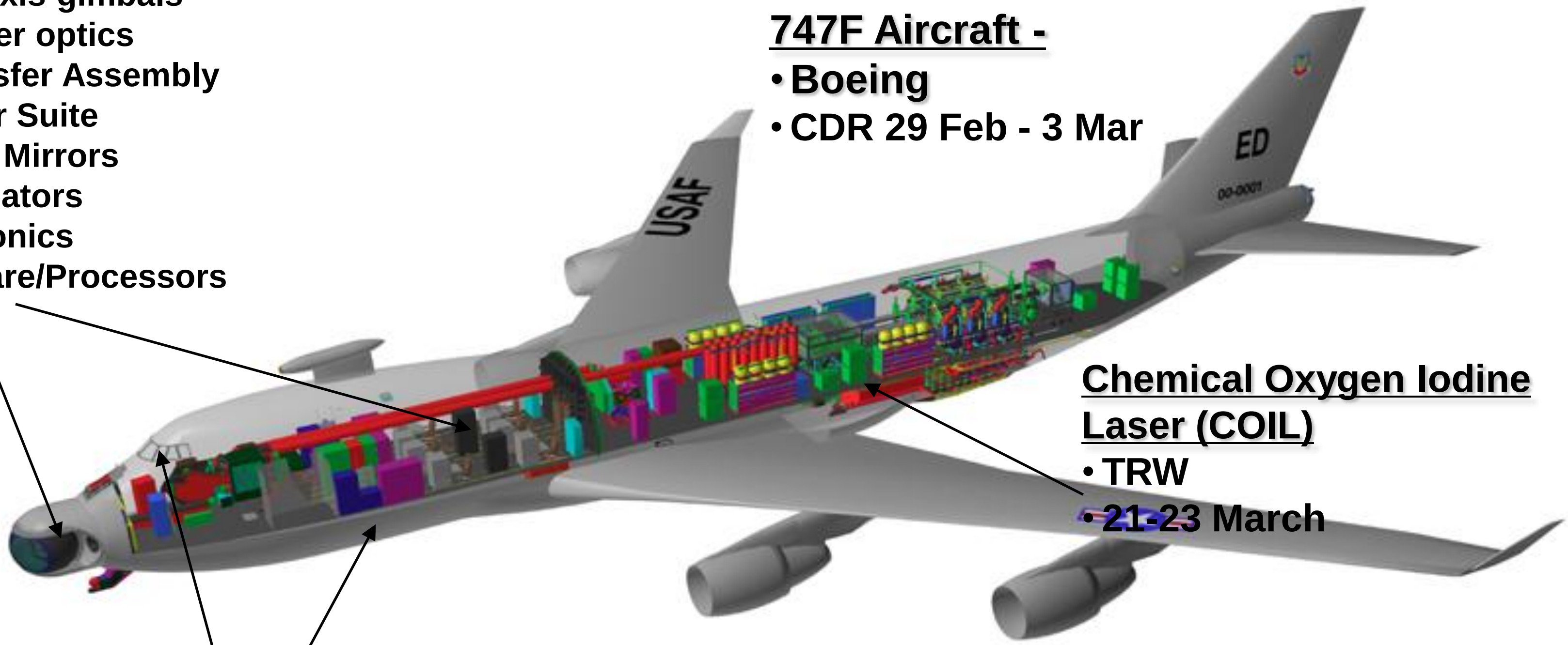


2nd stage separates and continues to destination

Fly-back booster

ABL System Design - collaboration with Lockheed - another example of using decomposition and MCC

- **AirBorne Laser – MDO method and multiprocessor computing were applied in this Lockheed project, a part of the national Strategic Defense Initiative**



Beam Control System

- Turret Assembly
  - Large Optics
  - Four Axis gimbals
  - Transfer optics
- Beam Transfer Assembly
  - Sensor Suite
  - Active Mirrors
  - Illuminators
  - Electronics
  - Software/Processors

System Level Design

- Boeing
- CDR 25-27 April

747F Aircraft -

- **Boeing**
- CDR 29 Feb - 3 Mar

Chemical Oxygen Iodine Laser (COIL)

- TRW
- 21-23 March

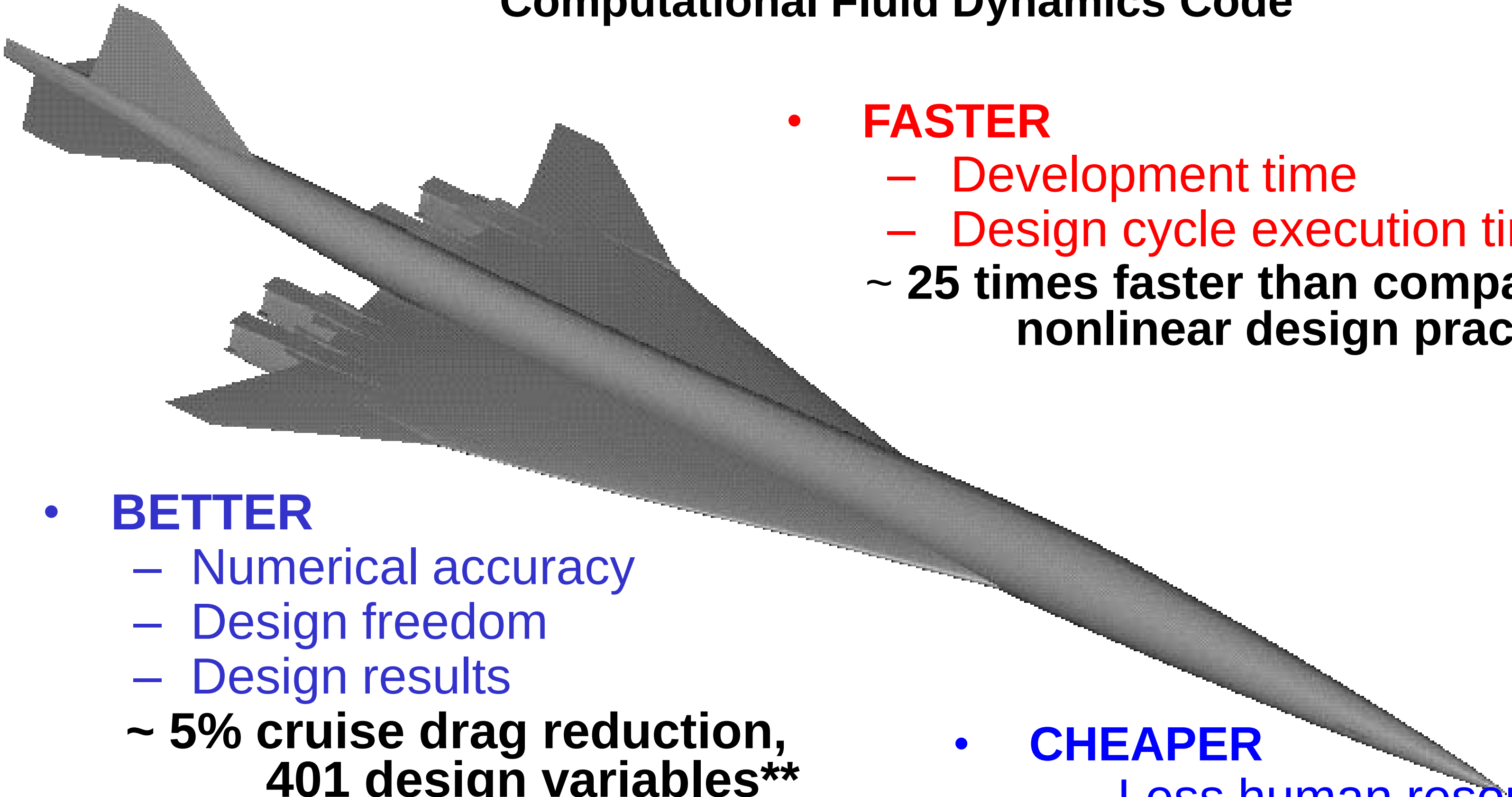
BMC^{4}I

- Boeing

- **Initially, the aim error exceeded specification**
- **MDO reduced aim error by 37 % at 2 % weight penalty and met specification**

High Speed Civil Transport Optimization

With ADJIFOR*-Generated CFL3D Adjoint Computational Fluid Dynamics Code



- **FASTER**
  - Development time
  - Design cycle execution time

~ 25 times faster than comparable nonlinear design practice**

- **BETTER**
  - Numerical accuracy
  - Design freedom
  - Design results

~ 5% cruise drag reduction, 401 design variables**

- **CHEAPER**
  - Less human resources
  - Less computer resources

~ 10 times cheaper than reference design cycle**

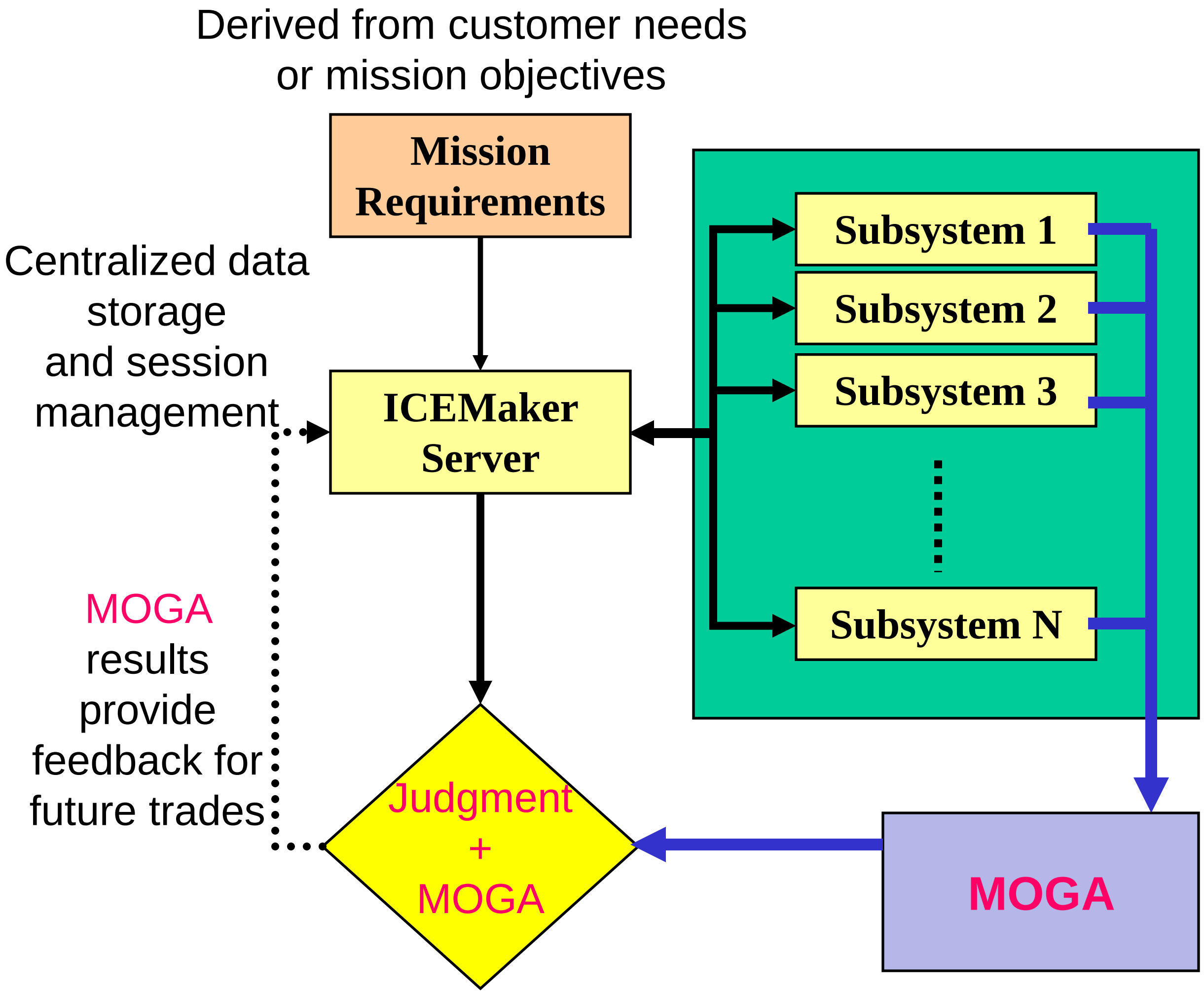
*** Developed by Rice University**

**** Initial Boeing Long Beach wing-body result**

MDO at Conceptual Design Stage

- Integrated Concurrent Engineering ICE implemented in ICEMaker: An Excel-Based Environment for Collaborative Design

- Multi-Objective Genetic Algorithm - MOGA



Derived from customer needs or mission objectives

Mission Requirements

Centralized data storage and session management

ICEMaker Server

Subsystem 1

Subsystem 2

Subsystem 3

Subsystem N

MOGA results provide feedback for future trades

Judgment + MOGA

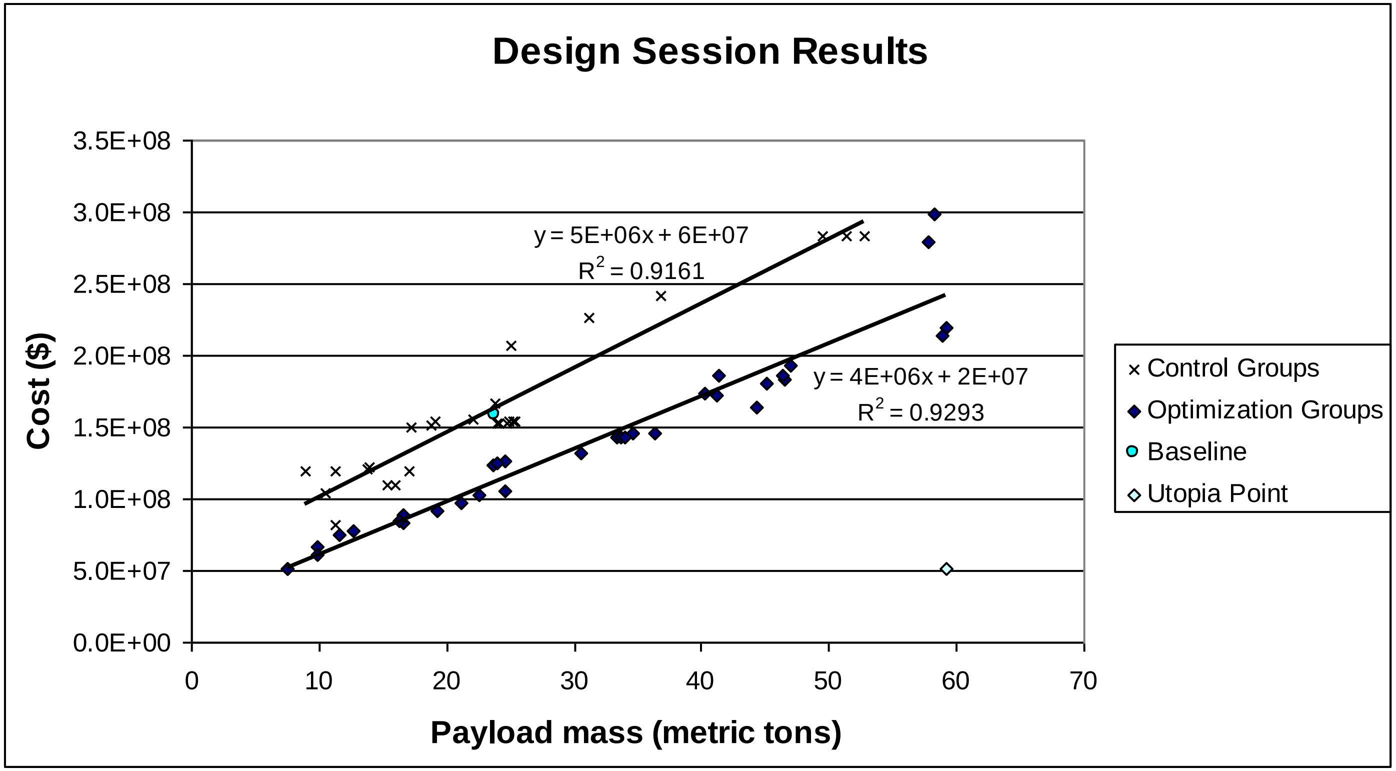
MOGA

- Collective and individual judgment retained as in ICE-only approach

- **The difference**: **Judgment amplified by the use of large volume of MOGA-generated, feasible designs, subsystem couplings accounted for.**

Comparison

- Test at MIT: Launch vehicle design project done simultaneously by ICE groups and ICE – GA augmented groups



- Each control group Pareto point is dominated by some Optimization group Pareto point
- No Optimization group Pareto point is dominated by a control group point
- The Optimization trendline for the combined groups is always closer to the utopia point than the control trendline
- Distance between trendlines measures MDO advantage

What MDO is not good at (yet) - 1

- **Discontinuities in math models**

  - Example: response with resonance divides design space into disjoint subspaces.

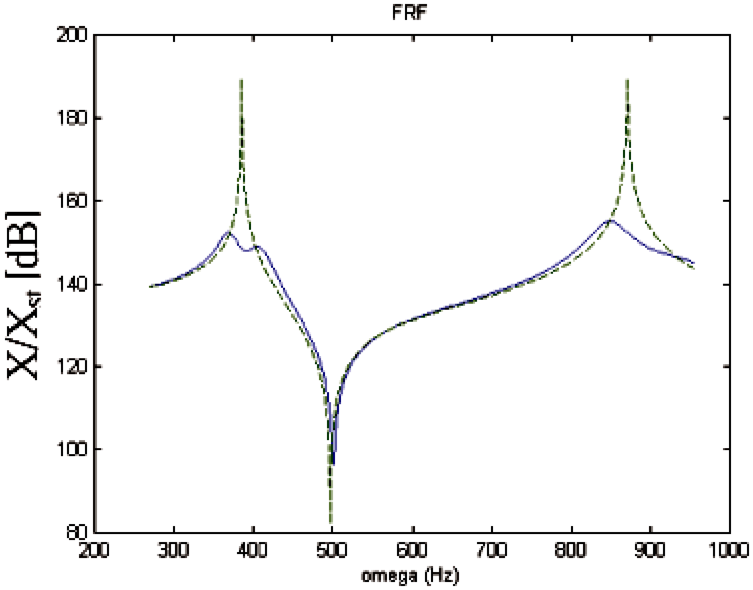
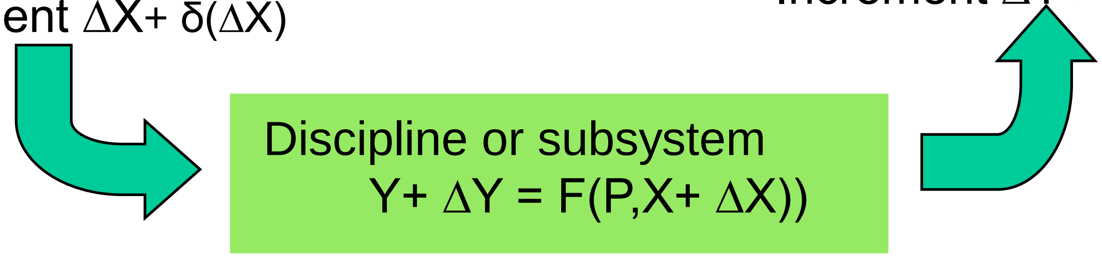


Figure 7- Amplitudes of the FRF dashed line: without DVA and shunts solid line: with DVA and shunts.

- CAVEAT: Approximate Math Models tend to hide discontinuities

What MDO is not good at (yet) - 2

- Optimization in presence of uncertainty δ
  - Constant parameters $P + \delta P$
  - Design Variables $X + \delta X$
  - Increment $\Delta X + \delta(\Delta X)$
  - State (behavior) variables $Y + \delta Y$
  - Increment $\Delta Y + \delta(\Delta Y)$



Discipline or subsystem

$Y + \Delta Y = F(P, X + \Delta X))$

- First order effect of δ uncertainty is the optimization result obtained as a (mean + distribution)

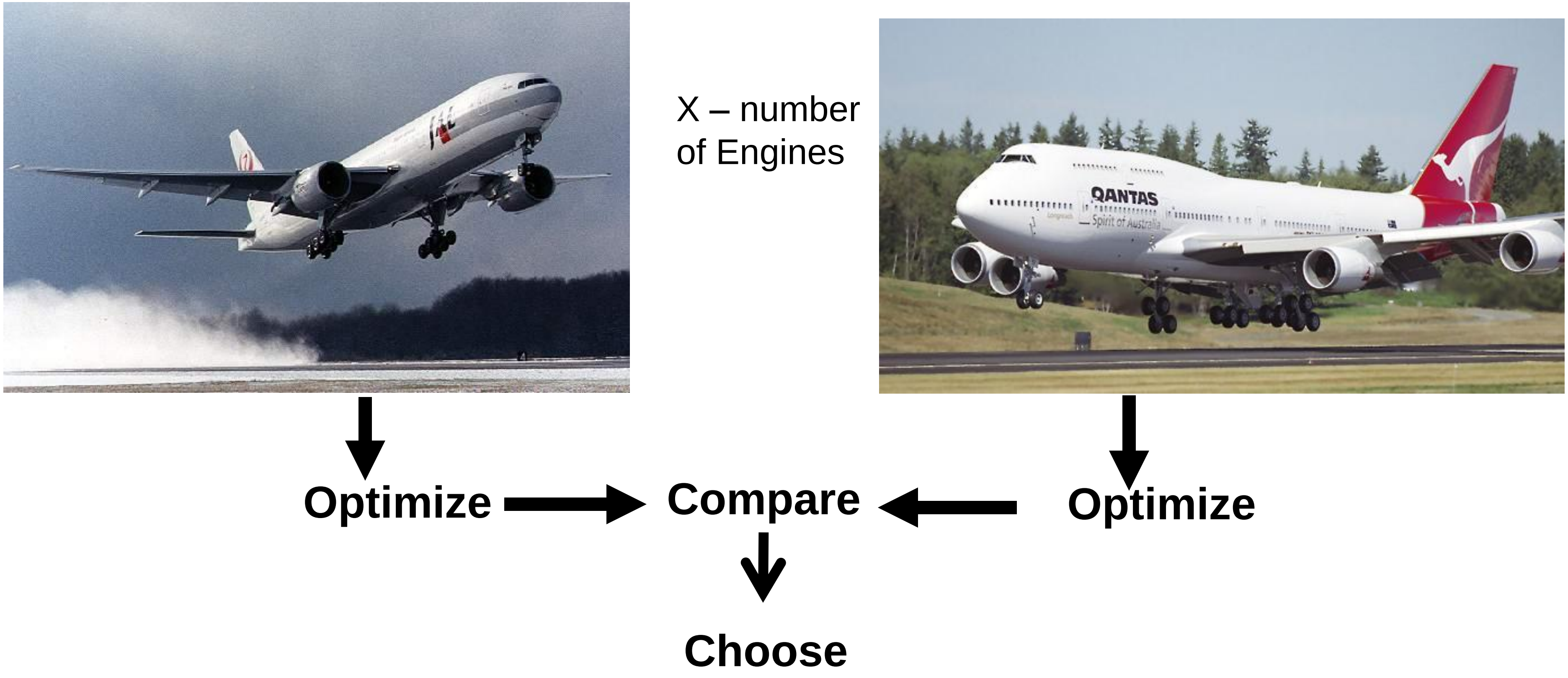
- Second order effect may be redirecting search path to qualitatively different optimum

- Even more difficult case arises when it is not clear what $F(P, X)$ is

- This is primarily a modeling issue at focus of current research

What MDO is not good at (yet) - 3

- ***Discrete* major design variables**



X – number of Engines

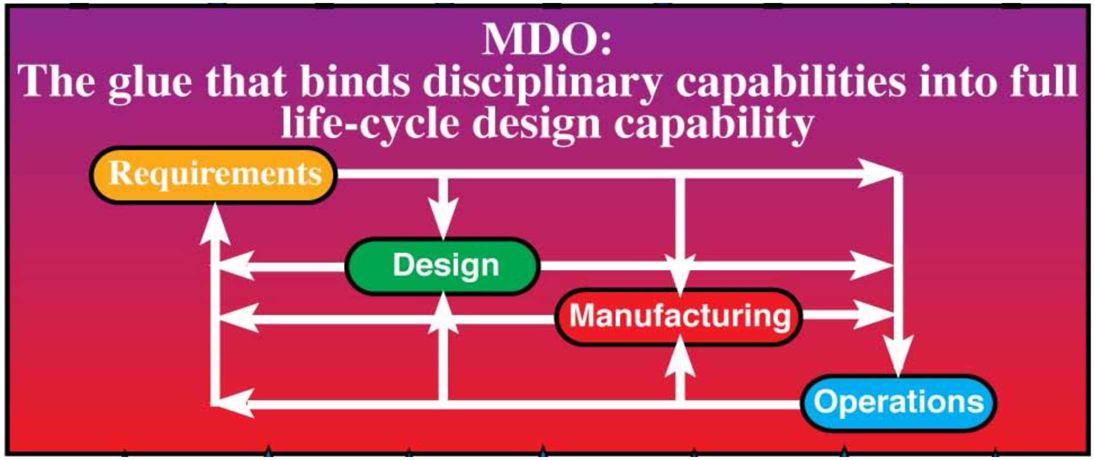
Optimize → **Compare** ← **Optimize**

Choose

- In contrast to *quasi-discrete* variables such as sheet metal thickness optimized as continuous variable and rounded up to the nearest commercial sheet metal gage available

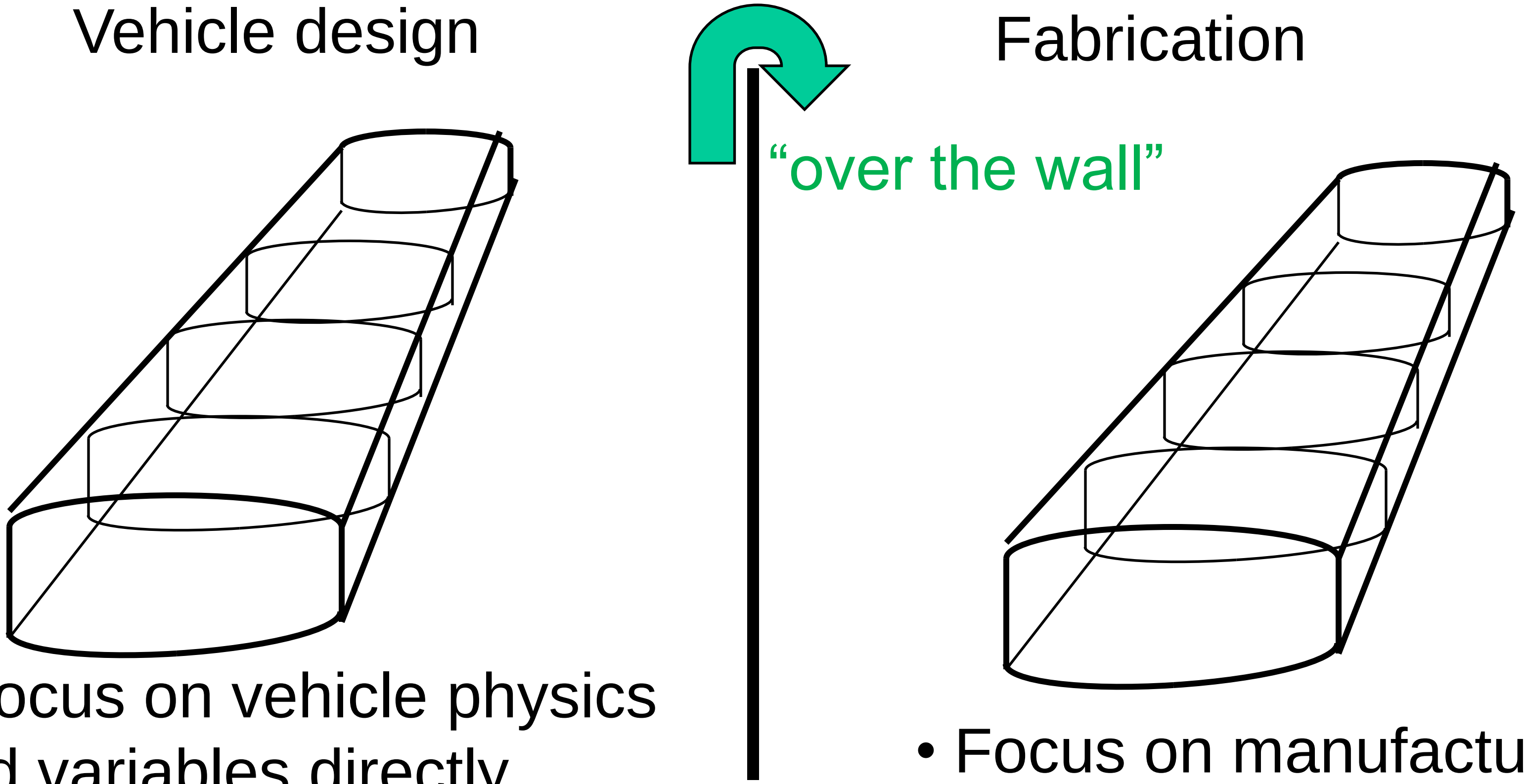
What MDO is not good at (yet) - 4

- Supporting design for entire Life Cycle



- Requirements to include ever more stringent environmental constraints, e.g., noise, emissions, etc.
- ***Eliminate barriers*** separating Life Cycle elements in design process
- Develop math models for elements of Life Cycle sharing design variables
- This is primarily a modeling and data exchange issue

Optimization Across Conventional Barriers: Potentially Very Important Advancement



Vehicle design

data

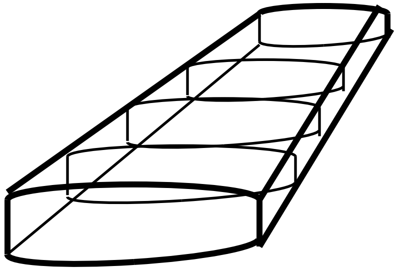
Fabrication

“over the wall”

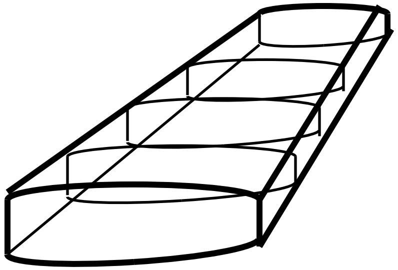
- Focus on vehicle physics and variables directly related to it
- E.g, range;
  wing aspect ratio

- Focus on manufacturing process and its variables
- E.g., cost;
  riveting head time

Two Loosely Connected Optimizations



- Seek design variables to maximize performance under constraints of:
  - Physics
  - Cost
  - Manufacturing difficulty



- Seek process variables to reduce the fabrication cost.

The return on investment (ROI) is a unifying factor

ROI = f(Performance, Cost of Fabrication)

Integrated Optimization

- Required: Sensitivity analysis on both sides

$\partial\text{Range}/\ \partial(\text{AspectRatio})$

$\partial\text{Cost}/\ \partial(\text{Rivet head time})$

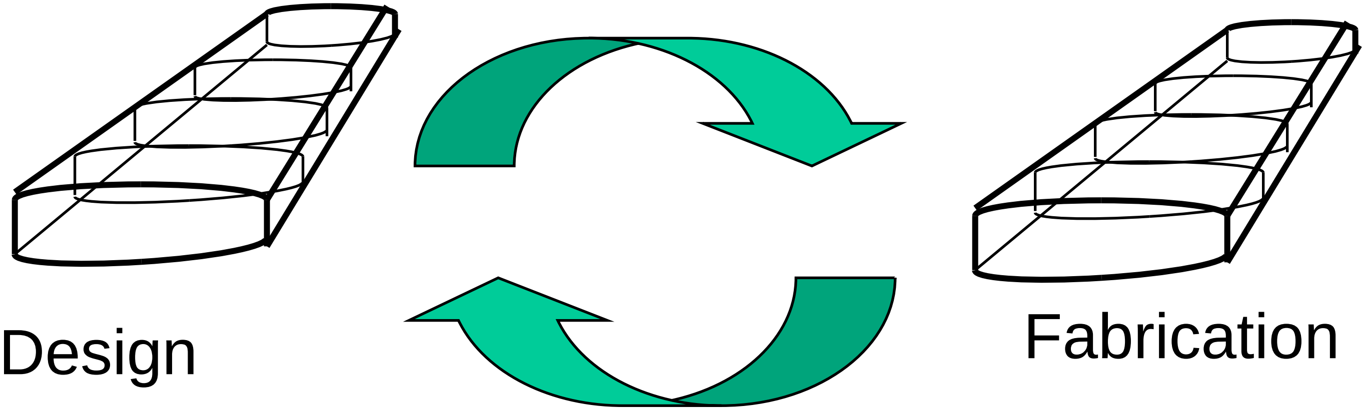
$\partial(\text{Rivet head time})/\ \partial(\text{Aspect Ratio})$

ROI = f(Range, Cost of Fabrication)

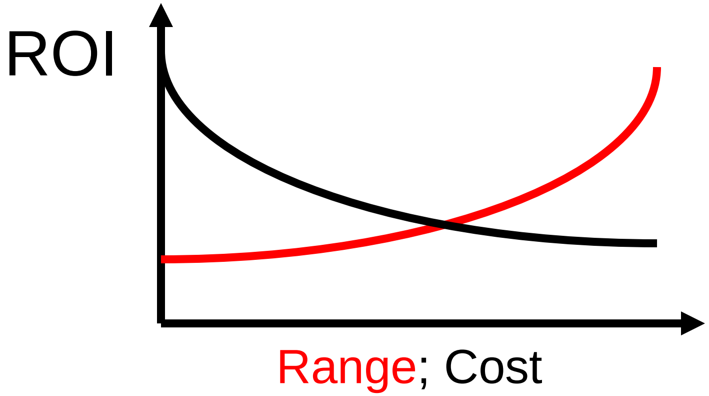
$\partial\text{ROI}/\ \partial\text{Aspect Ratio} = (\ \partial\text{ROI}/\ \partial\text{Cost})\ ((\partial\text{Cost}/\ \partial(\text{Rivet h.t.}))$
$(\partial(\text{Rivet h.t})/\ \partial(\text{Aspect Ratio})) + (\partial\text{ROI}/\partial\text{Range})\ (\partial\text{Range}/\partial(\text{Aspect Ratio}))$

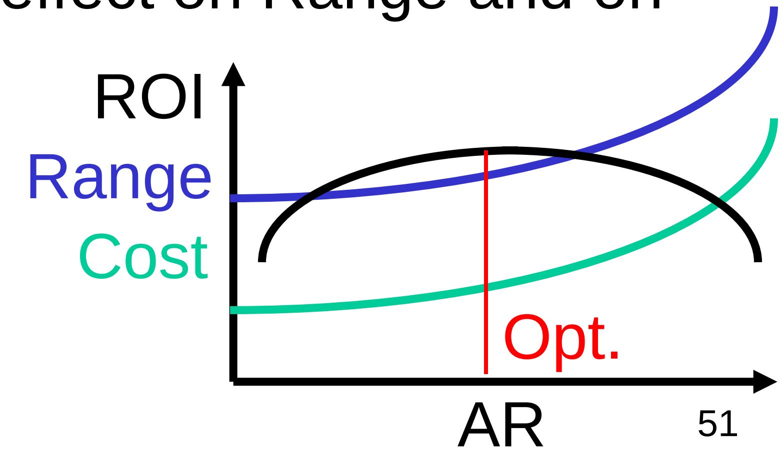
Integrated Optimization Design < --- > Fabrication

- Given the derivatives on both sides



- Unified optimization may be constructed to seek vehicle design variable, e.g., AspectRatio, for maximum ROI incorporating AR effect on Range and on fabrication cost.

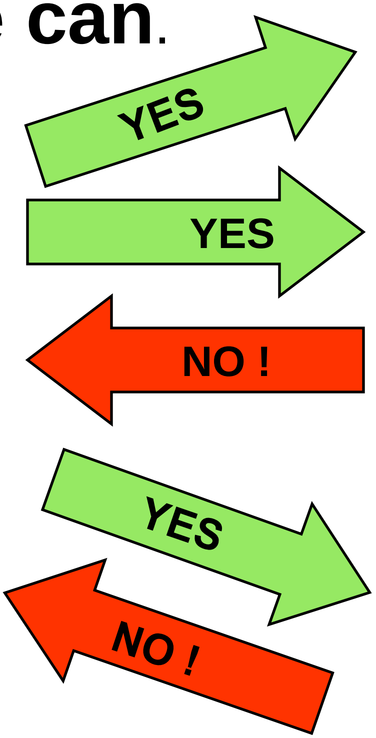




What MDO is powerless to do

- **Optimization Cannot Get Something that Was Not Seeded.**
- **In contrast, people can.**

Start



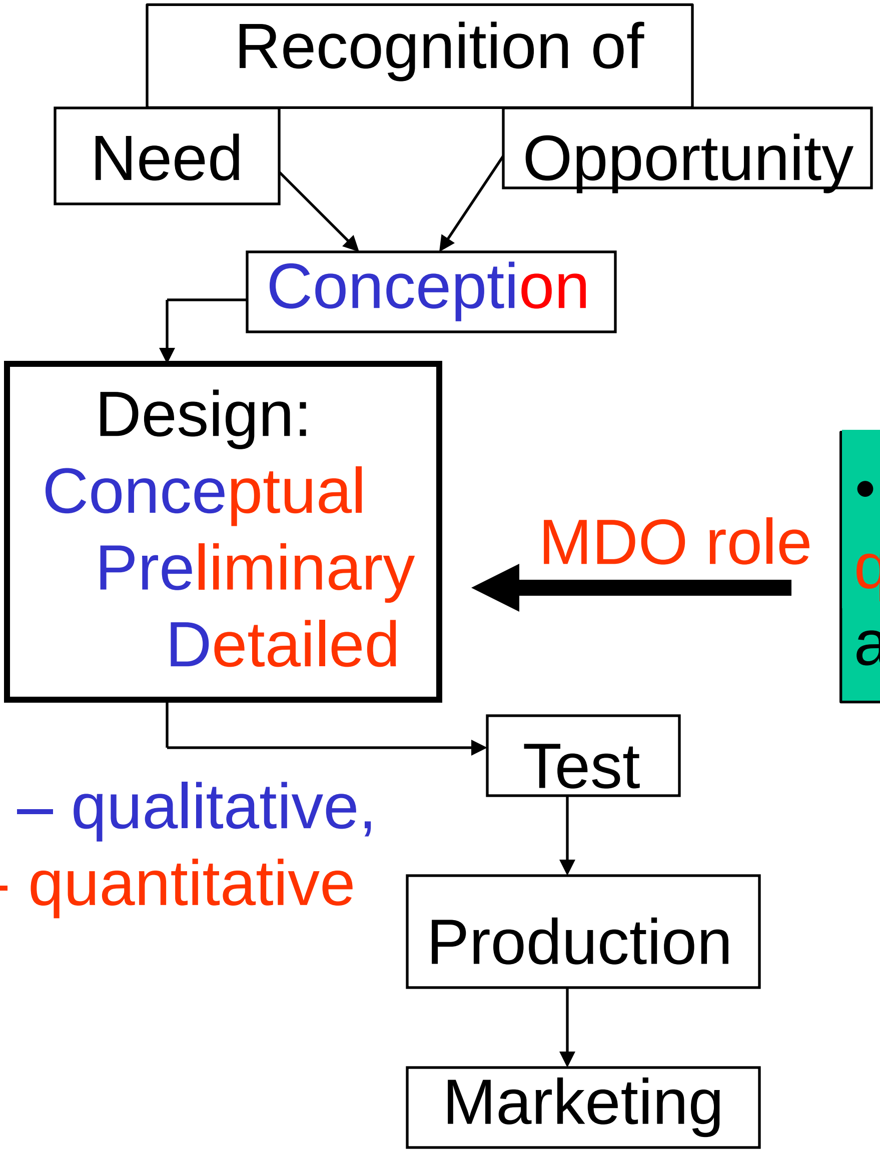
Get

Get

Get

- **If design space could be extended and redefined, MDO would advance from design-aid status to *automated designer***
- **Prerequisite: understanding of the human mind and brain**

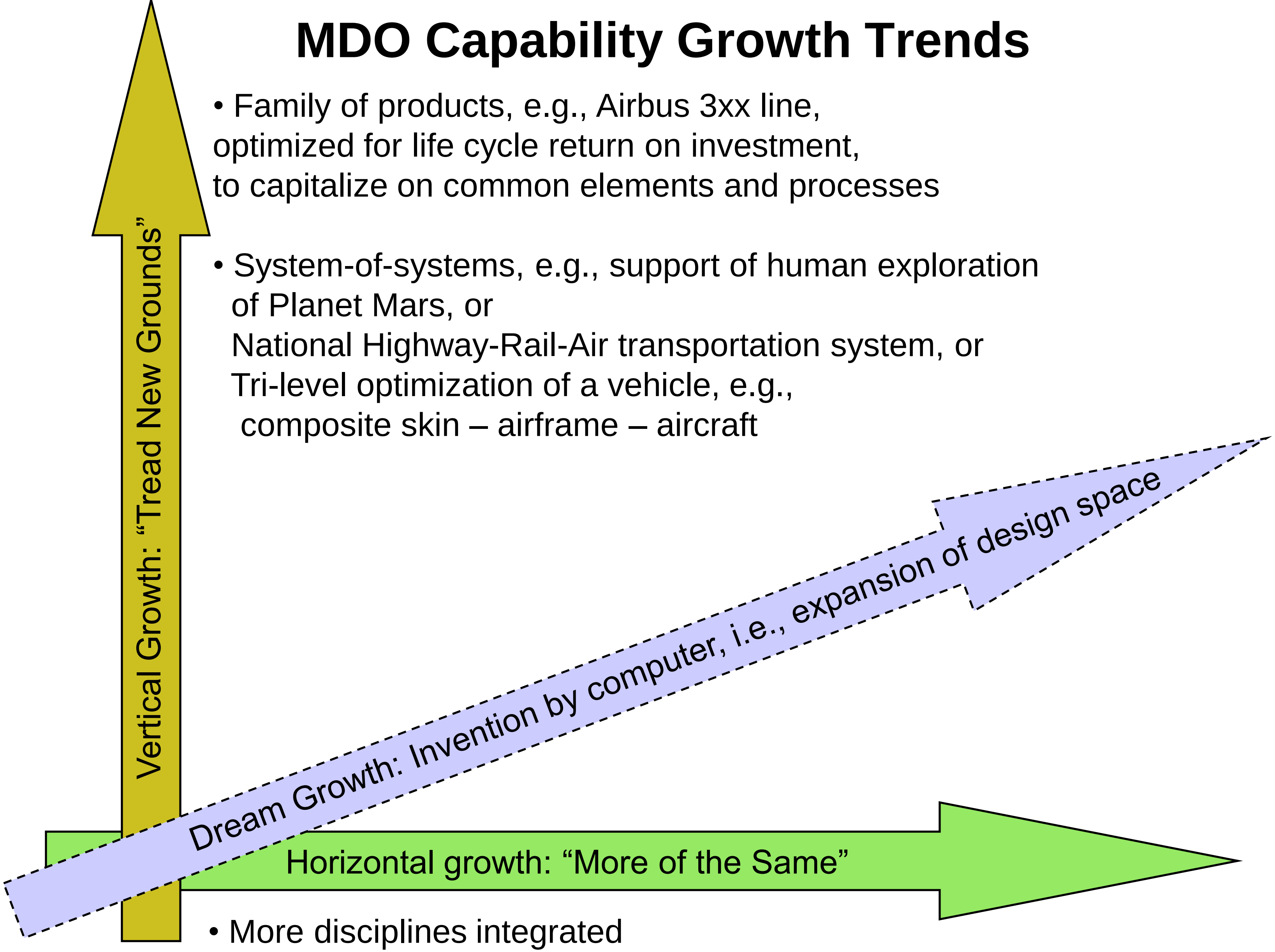
MDO Role in Product Life-Cycle



- MDO excels as a quantitative tool that aids human judgment

blue – qualitative,
red - quantitative

MDO Capability Growth Trends



- Family of products, e.g., Airbus 3xx line,
optimized for life cycle return on investment,
to capitalize on common elements and processes

- System-of-systems, e.g., support of human exploration
of Planet Mars, or
National Highway-Rail-Air transportation system, or
Tri-level optimization of a vehicle, e.g.,
composite skin – airframe – aircraft

Vertical Growth: “Tread New Grounds”

Dream Growth: Invention by computer, i.e., expansion of design space

Horizontal growth: “More of the Same”

- More disciplines integrated
- Growth of dimensionality: more variables, constraints, objectives
- Incorporation of life cycle considerations, including uncertainties
- Solving problems with discontinuities
- Faster answers due to MCC

Summary and Conclusions

- Multidisciplinary Design Optimization (MDO) has evolved as a research and development field engaging:
  - Engineering Physics
  - Numerical Methods
  - Modeling & Simulation
  - Operations Research
  - Computer Science
  - Management Science
  - Human Factors
  - CAD
- MDO offers mature capability in disciplines and their integration in projects
- **Recent advances made MDO ready to aid in large undertakings at major product level involving large company and its partnerships**
- Areas exist where MDO is inadequate qualitatively and quantitatively, **these areas identify priority development trends**
- MDO is poised to impact design of product families and system-of-systems
- Multiprocessor computing and MDO are synergistically intertwined toward rapid growth of MDO capability
- Advancement of MDO from designer's aid to automated designer is a "over the horizon" proposition, predicated on success of research into human mind and brain

Recommended Supplemental Reading: next chart

Supplemental Reading

TEXTS:

- Rao, Singiresu S.: “Engineering Optimization, Theory and Practice” John Wiley & Sons, 1996
- Haftka, Rafael. T..; Gurdal, Zafer : “Elements of Structural Optimization”, Kluwer Acad. Publ. 1991
- **SURVEYS**
- **Sobieszczanski-Sobieski, J.: and Haftka, R.T.: Multidisciplinary Aerospace Optimization: Survey of Recent Developments; AIAA-96-0711, Structural and Multidisciplinary Optimization J., Vol.14, No.1, August 1997**
- **Balling, R.J.; and Sobieszczanski-Sobieski, J.: Optimization of Coupled Systems: A Critical Overview of Approaches; AIAA J. Vol. 34, No. 1, pp. 6-17; 1996.**
- **ARTICLES**
- Sobieszczanski-Sobieski, J. , Barthelemy, J.-F. M. , and Riley, K. M.: Sensitivity of Optimum Solutions to Problem Parameters. AIAA Journal, Vol. 20, No. 9, Sept.1982, pp 1291-1299.
- Sobieszczanski-Sobieski, Jaroslaw: On the Sensitivity of Complex, Internally Coupled Systems. AIAA Paper 88-2378, NASA TM 100537 and
- AIAA Journal, vol. 28, No. 1, Jan. 1990, pp. 153-160.
- "Everything Influences Everything Else: How Math Can Help to Resolve Designer's Dilemma" by Jaroslaw Sobieszczanski-Sobieski, NASA Langley Research Center and Jan Tulinius, Rockwell International; AA Magazine, May 1991
- Multidisciplinary Design Optimization: An Emerging New Engineering Discipline by Jaroslaw Sobieszczanski-Sobieski NASA Langley Research Center Hampton, Virginia, First World Congress on Structural Optimization, Rio de Janeiro, July 1993, ed. J. Herskovits; Proceedings of; Kluwer Acad. Publ. pp.483-496, 1995
- Sobieszczanski-Sobieski, J.; Altus, T., Phillips, M.; and Sandusky, R., Jr.: “Bi-Level Integrated System Synthesis for Concurrent and Distributed Processing (BLISS 2000)”; AIAA-2002-5409; 9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Sept. 4-6, 2002, Atlanta, Georgia and AIAA Journal, Vol. 41, No. 10, Oct. 2003, pp. 1996-2003.
- Jaroslaw Sobieski and Olaf Storaasli: "Computing at the speed of Thought" Feature article in Aerospace America, Oct. 2004, pp.35-38.
- Sobieszczanski-Sobieski J., Venter G.: "Imparting desired attributes in structural design by means of multi-objective optimization"; AIAA 2003-1546; and Structural and Multidisciplinary Optimization, Vol. 29; No. 6; June 2005, pp. 432-444
- Brian Bairstow; Olivier DeWeck, and Jaroslaw Sobieszczanski-Sobieski “Analysis of Integration of System-Level Optimization in Concurrent Engineering” 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, April 23-26, Honolulu, Hawaii.AIAA 2007-1879
- de Weck, O.; Agte, J.; Sobieszczanski-Sobieski, J.; Arendsen, P; Morris, A.; and Spieck, M.: “State- of- the- Art and Future Trends in Multidisciplinary Design Optimization”;
- AIAA-2007-1905; 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference; April 23-26, 2007, Honolulu, HI

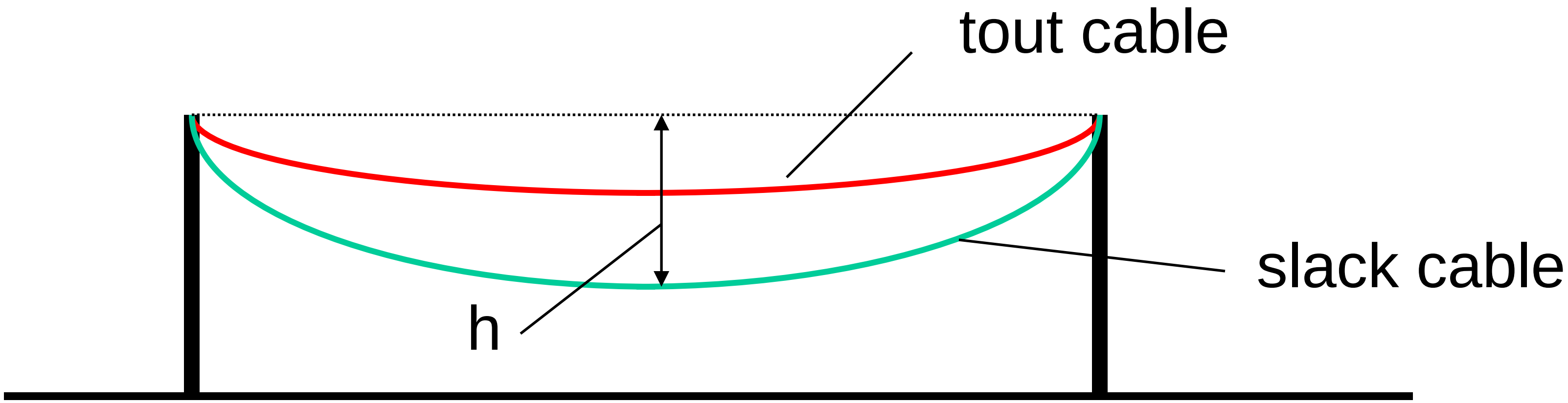
The End

Thank you

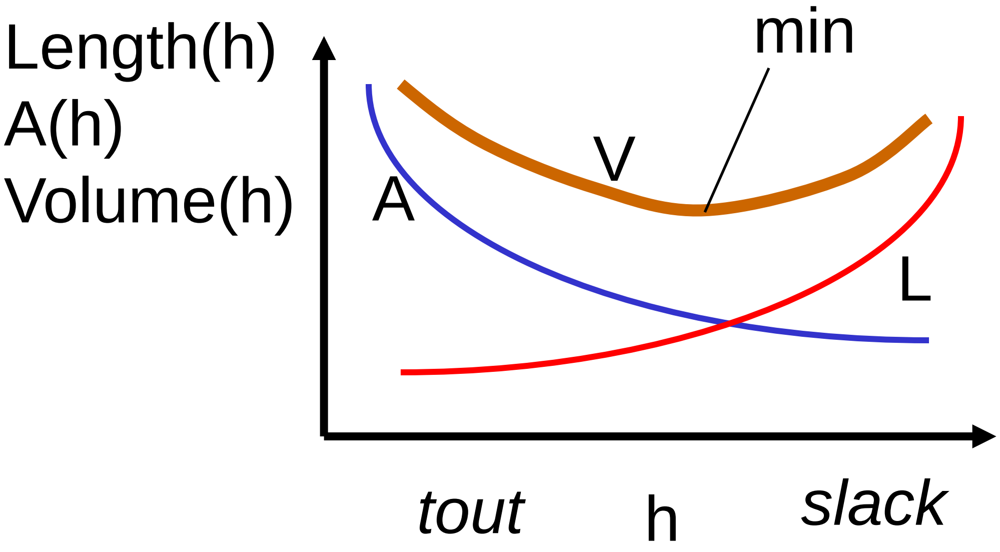
Q & A

Spares

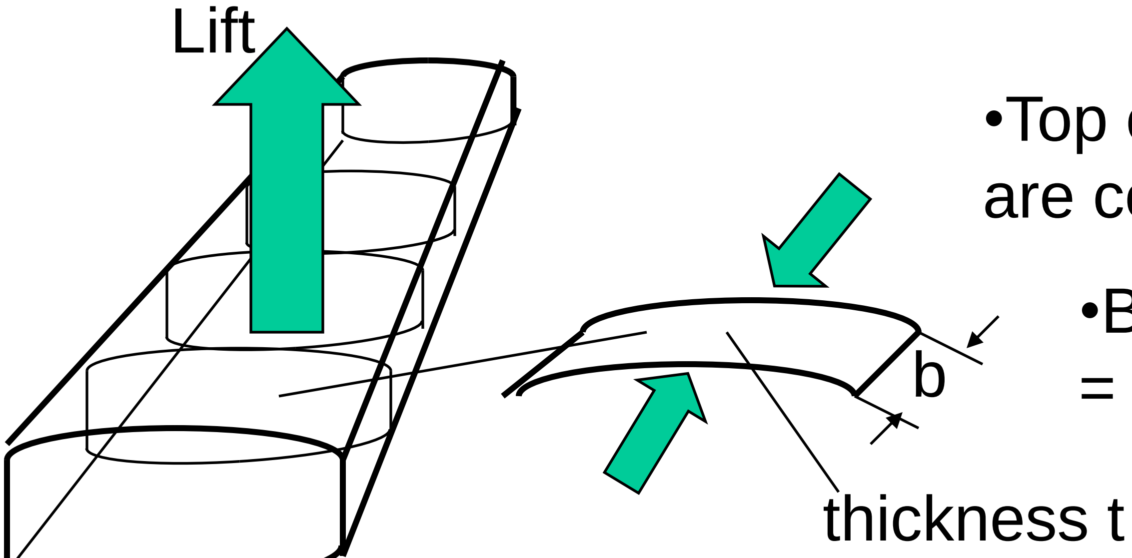
Power Line Cable



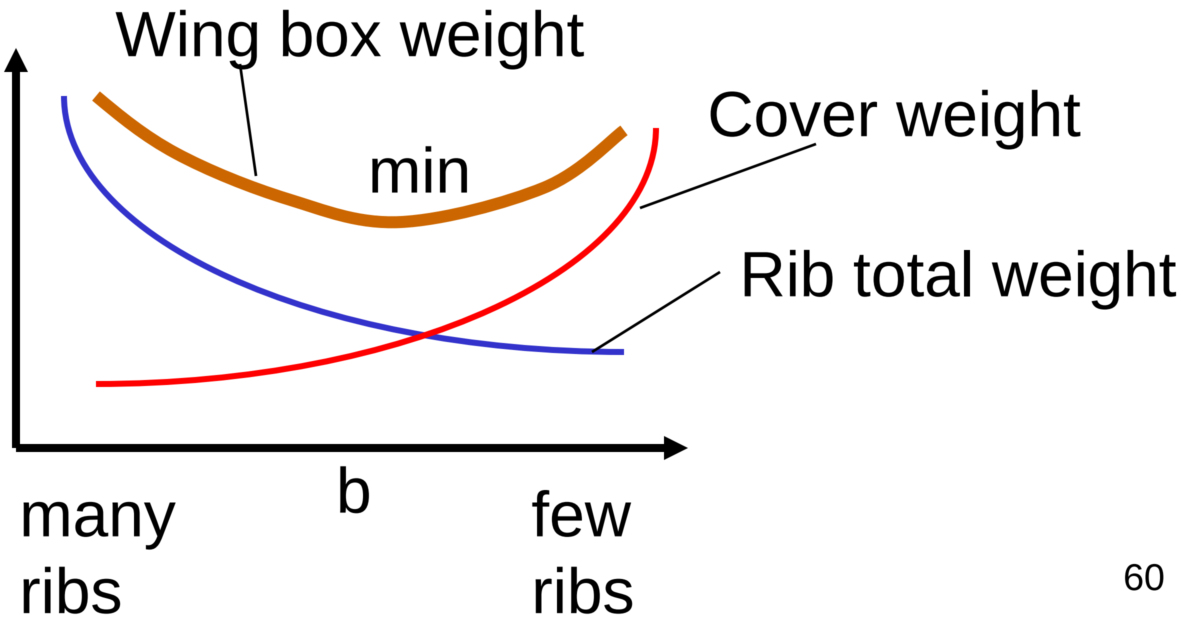
- Given:
  - Ice load
  - self-weight small
  - h/span small



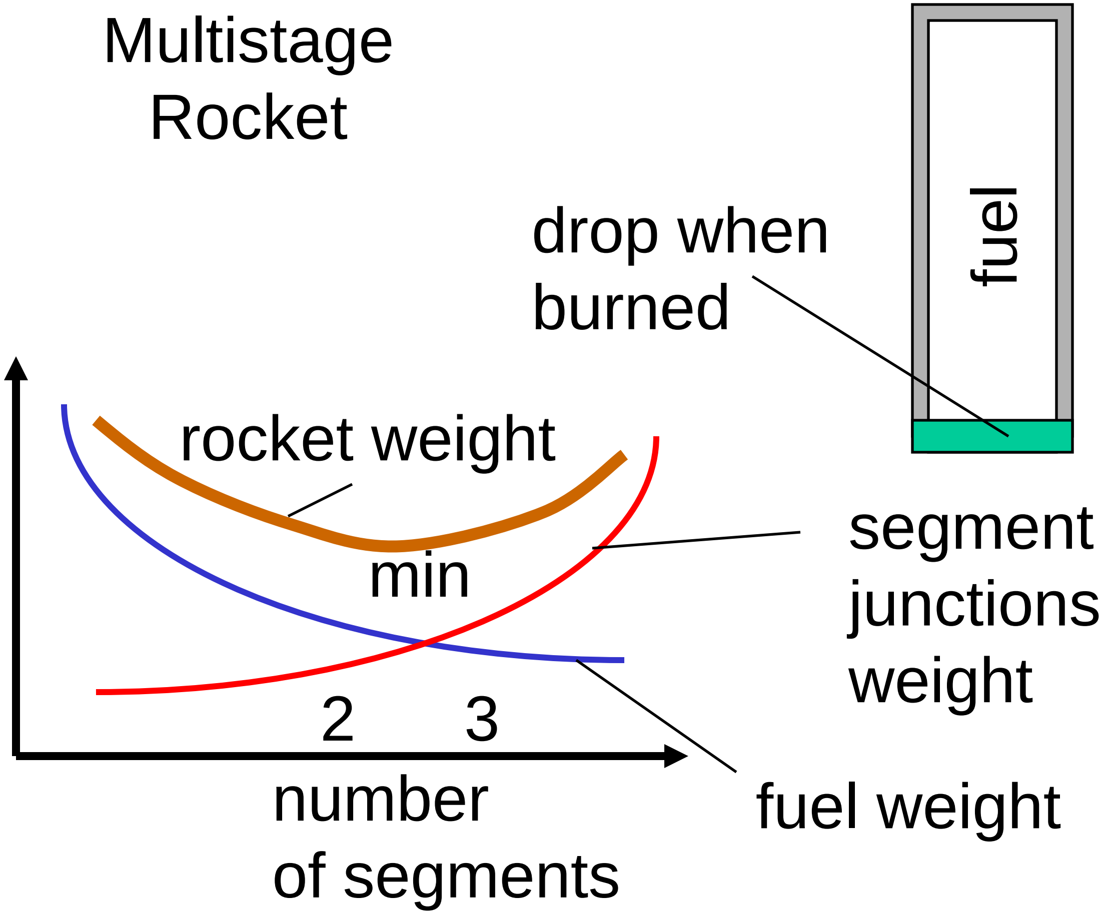
Wing Thin-Walled Box



- Top cover panels are compressed
- Buckling stress $= f(t/b)^2$



Multistage Rocket



drop when burned

fuel

rocket weight

min

segment junctions weight

2

3

fuel weight

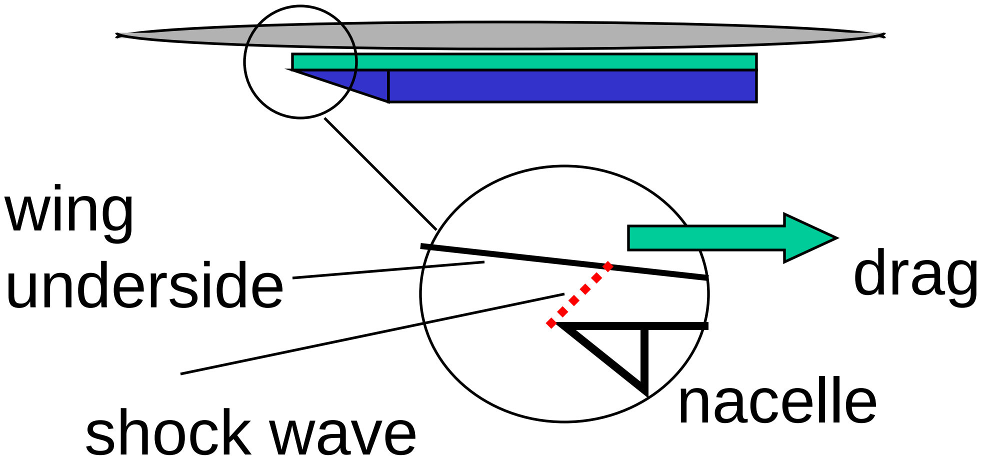
number of segments

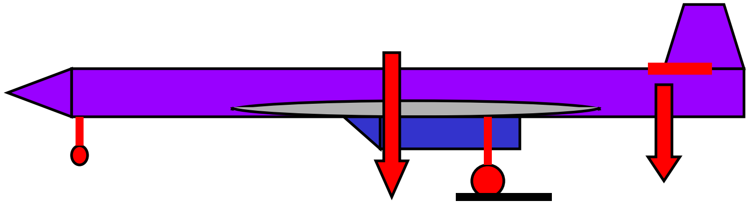
- More segments (stages) = less weight to carry up = less fuel
- More segments = more junctions = more weight to carry up
- Typical optimum: 2 to 4.

[redacted]

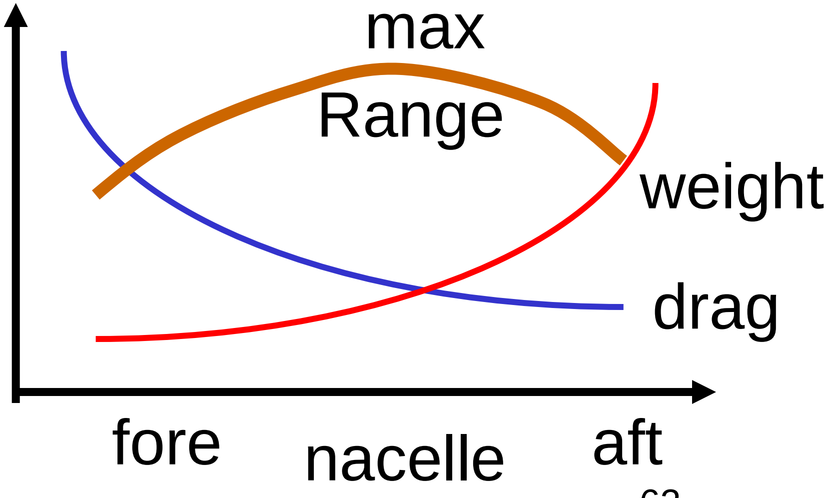
Saturn V

Under-wing Nacelle Placement

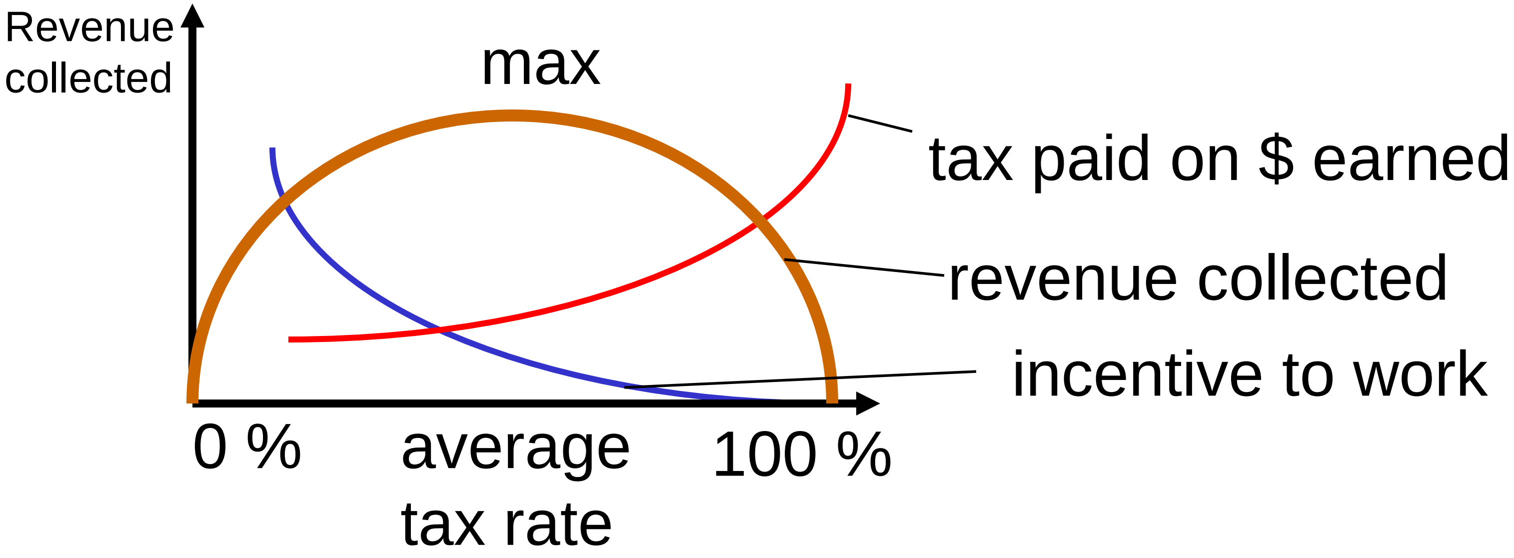




- Inlet ahead of wing max. depth = shock wave impinges on forward slope = drag
- Nacelle moved aft = landing gear moves with it = larger tail (or longer body to rotate for take-off = more weight



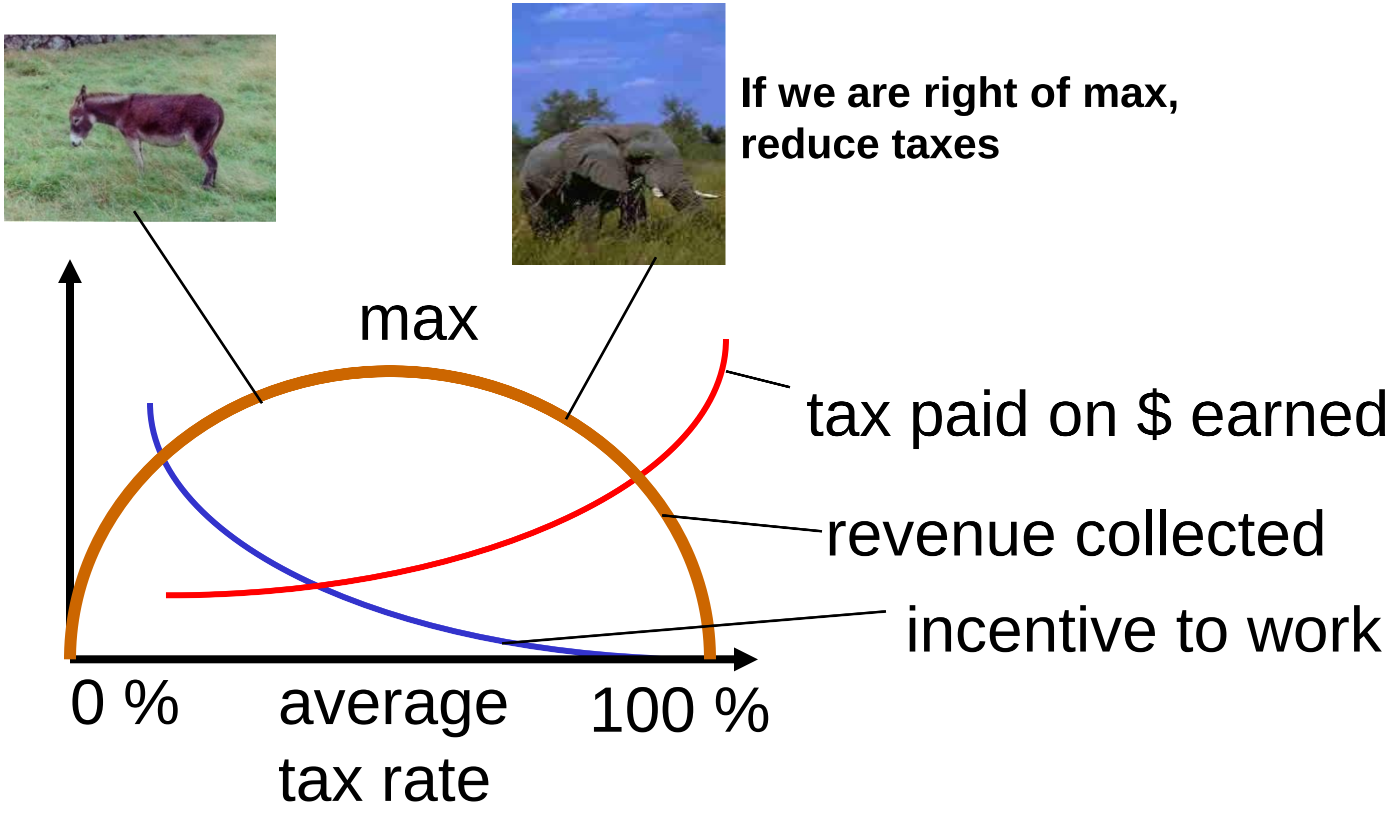
National Taxation



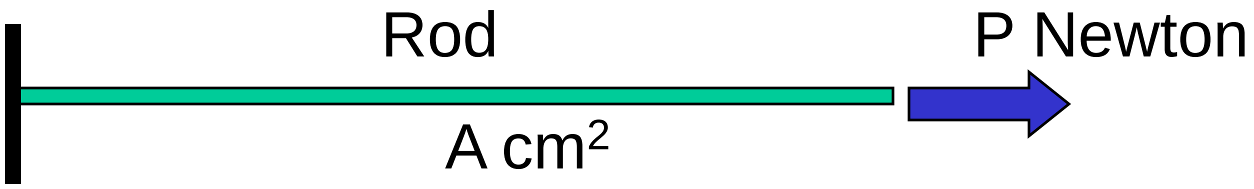
National Taxation
Increase taxes? Cut taxes?

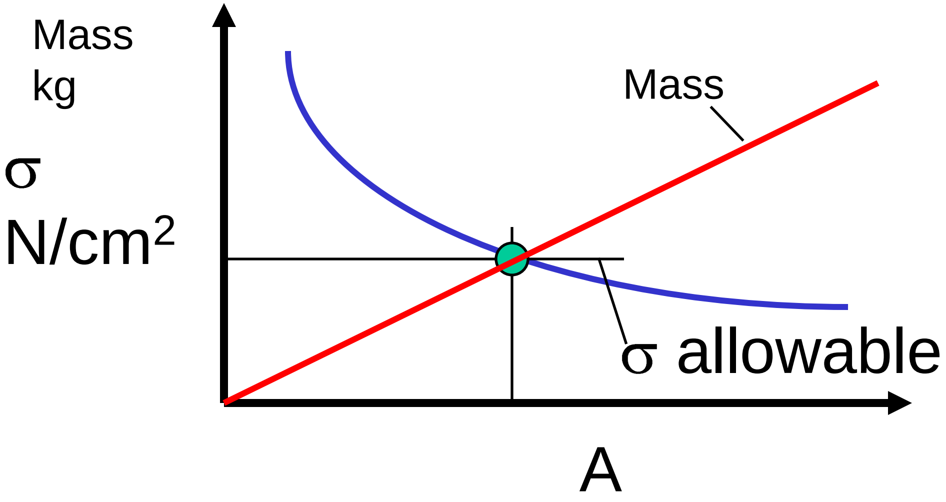
If we are left of max, increase taxes

If we are right of max, reduce taxes



Nothing to Optimize



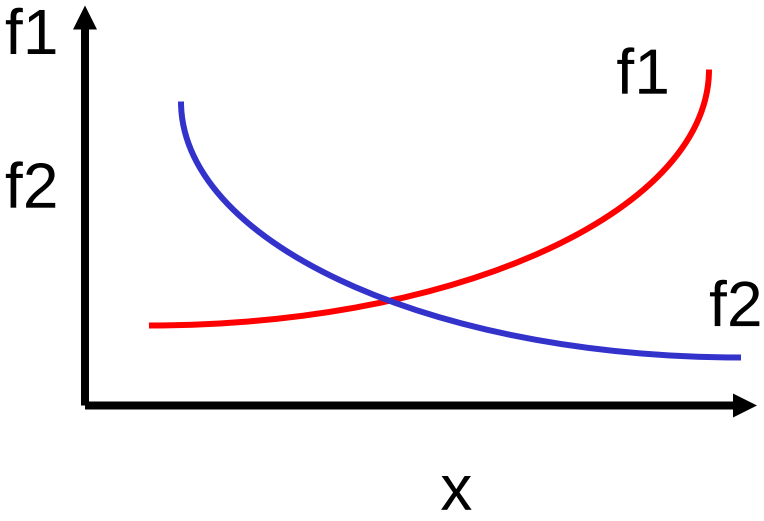


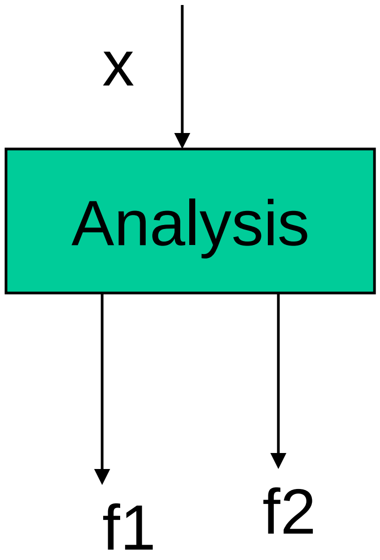
- Monotonic trend
- No counter-trend
- Nothing to optimize

How to recognize that the problem at hand needs optimization.

- General Rule of the Thumb:

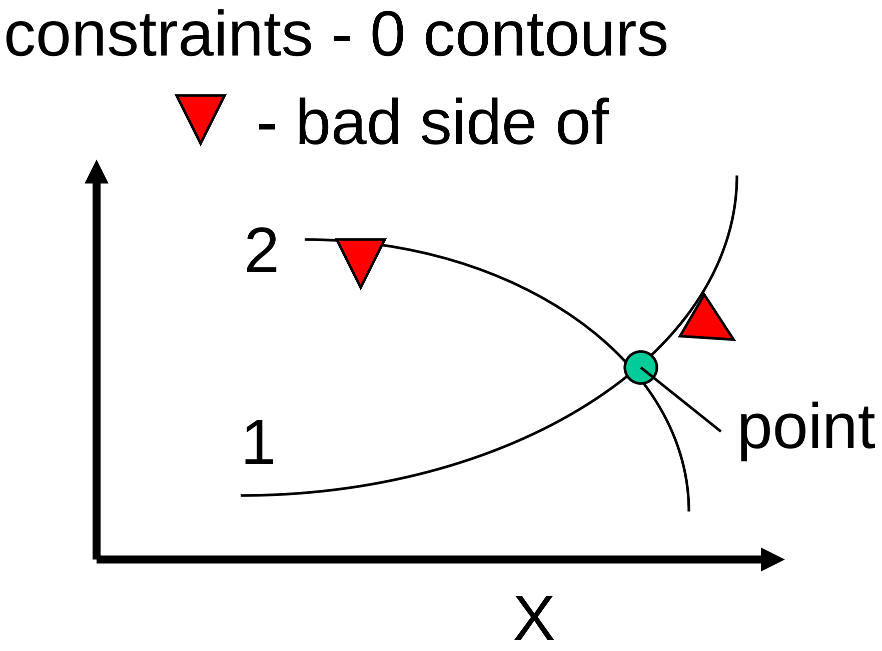
there must be at least two opposing trends as functions of a design variable

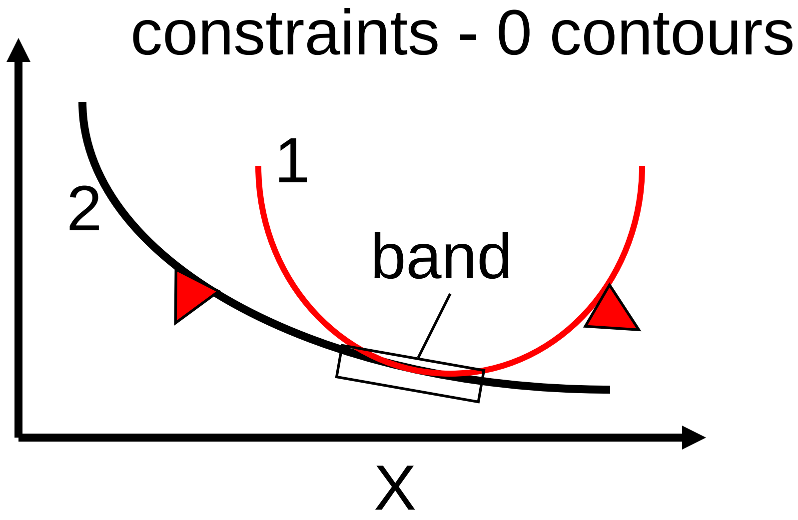


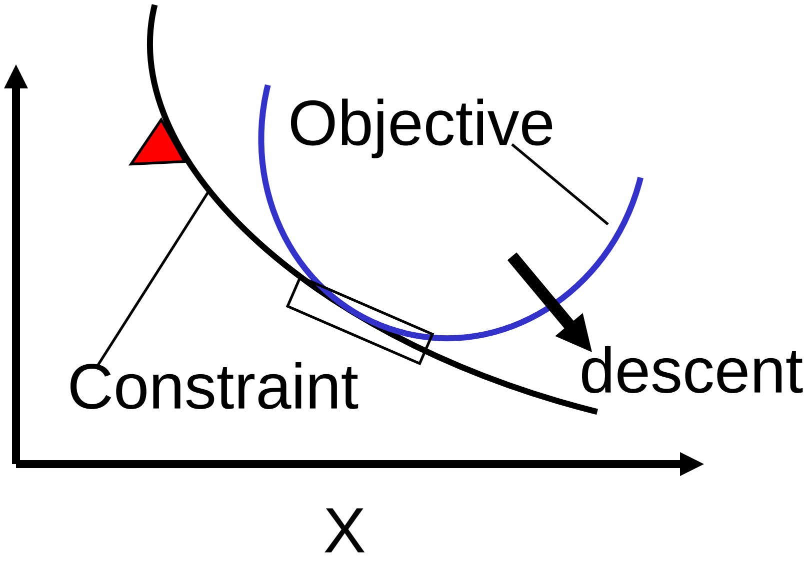


Various types of design optima

Design Definition: Sharp vs. Shallow

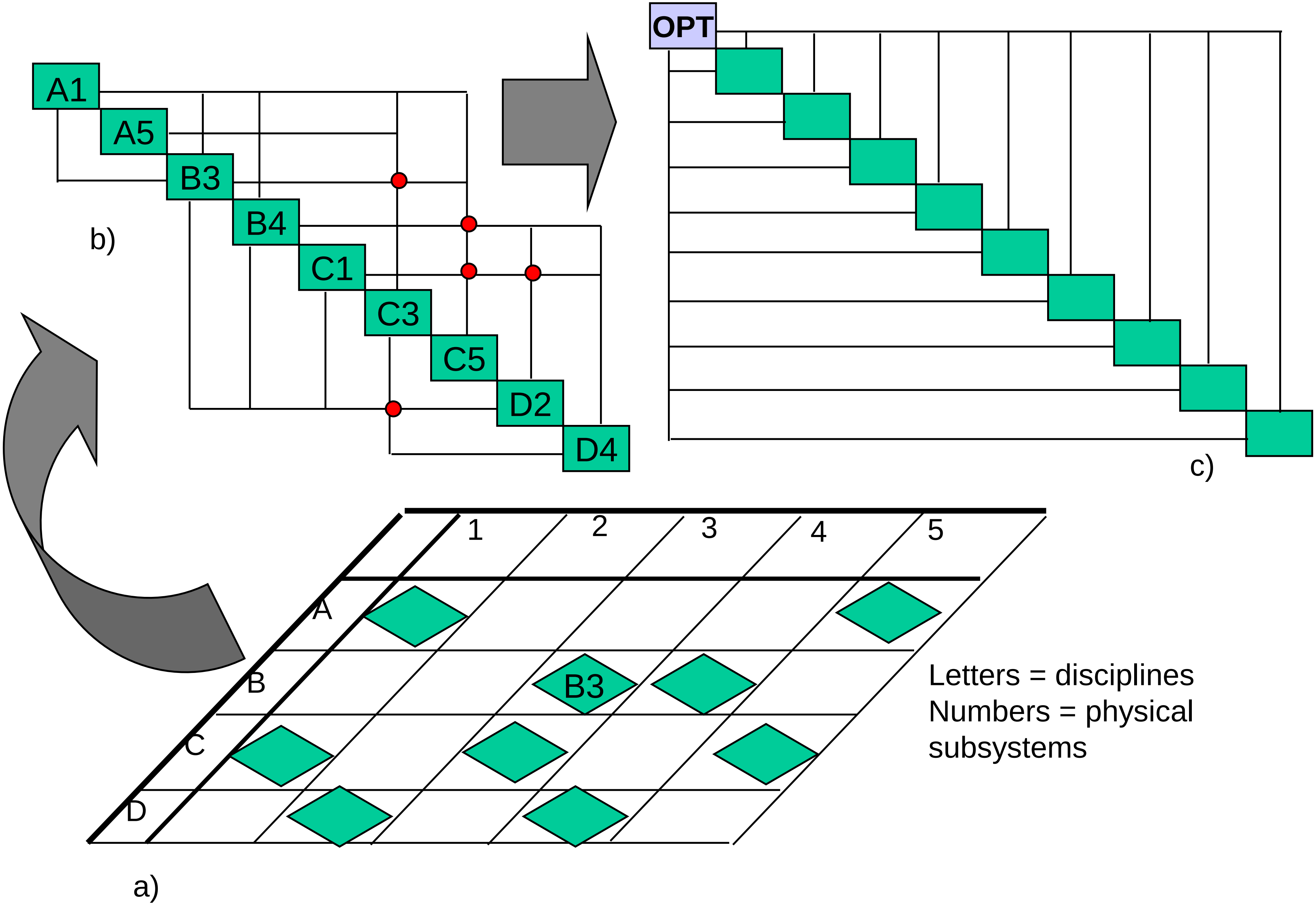






- Near-orthogonal intersection defines a design point

- Tangential definition identifies a band of of designs



Letters = disciplines
Numbers = physical subsystems

Figure 1 BLISS supporting a project matrix organization

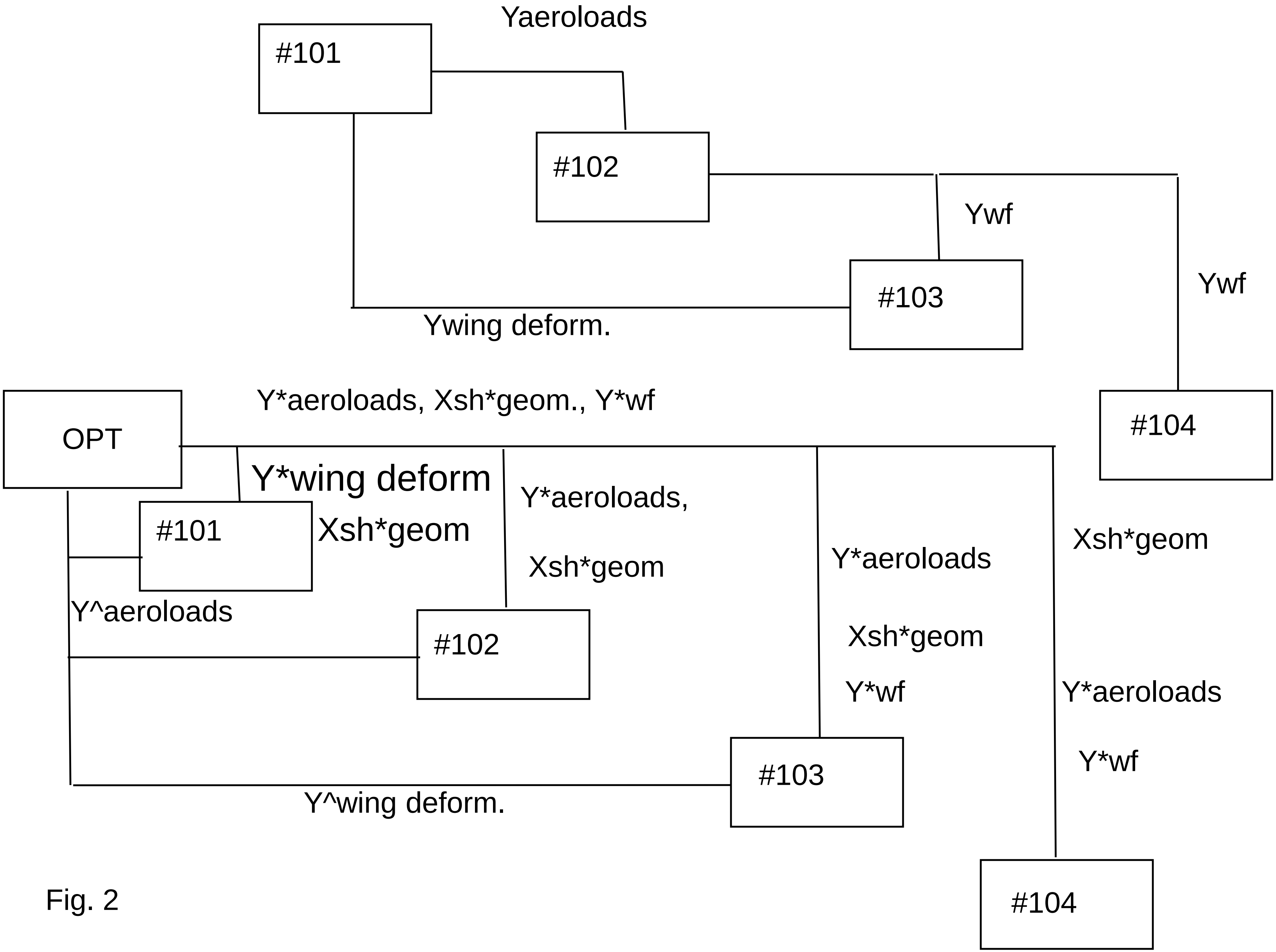
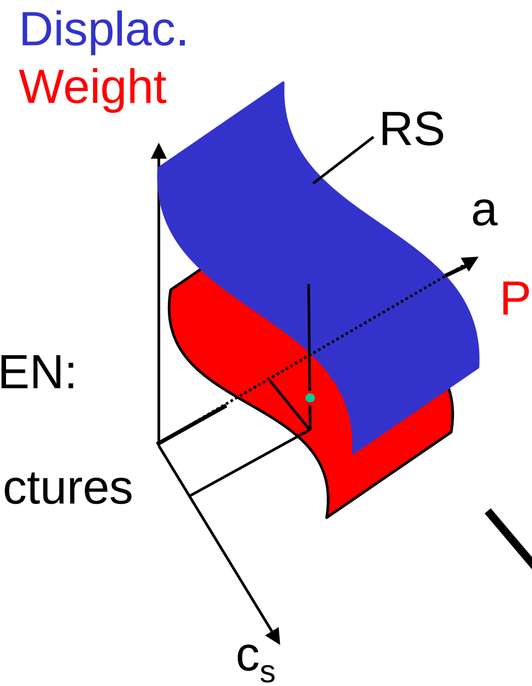

Yaeroloads
#101
#102
Ywf
#103
Ywf
Ywing deform.
Y*aeroloads, Xsh*geom., Y*wf
OPT
#104
Y*wing deform
#101
Xsh*geom
Y*aeroloads,
Xsh*geom
Y*aeroloads
Xsh*geom
Y*wf
Xsh*geom
Y*aeroloads
Y*wf
Y^aeroloads
#102
#103
Y^wing deform.
#104

Fig. 2

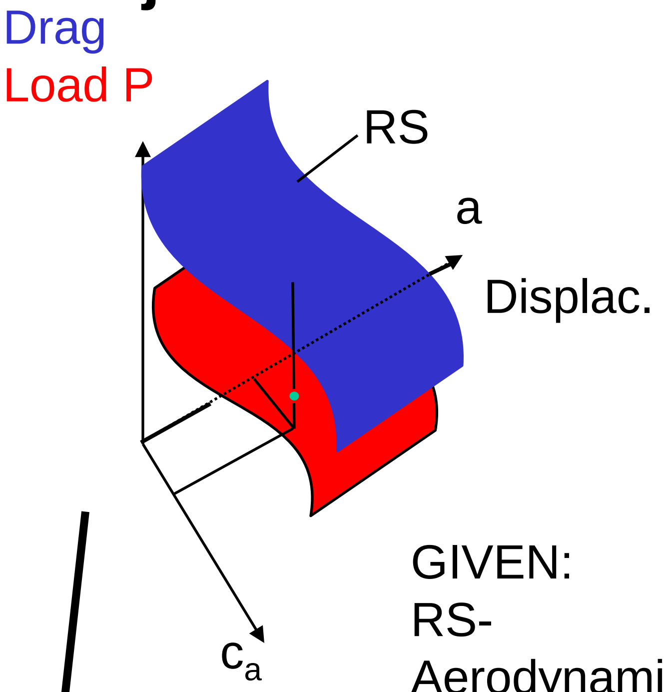
Themes

- 1 Title
- 2 Hist
  - 3-5 Review of Syllabus
  - 6-7 Migration to other disc. and MDO
- 8-12 Design Process attributes
- 13-24 Design Process requires infrastructure capable of:
  - 13 Agility and Huge Volumes of Variables
    - 14 Solution to the above: Approximations, Decoupling Analysis from Opt.
    - 15-16 Application example: Boeing Hypersonic
  - 17-18 Everything affects…
    - 19-20 GSE as solution for the above based on discipl. Sensit. - syllabus.
  - 21 Data handling
    - 22-23 Nsq Diag- sol. For the above
- 24 Human factors
- 26 Help from MCC
- 27 Commercial tools
- 27-40 Two Implementations of MDO based on all of the above
  - 27-28 ICE
  - 29 breaking the sequentiality
  - 30 dilemma resulting from the above
  - 31-40 BLISS
- 41-45 What is not good - needs to be done
- 46-48 Closure

System-level Optimization, the objective from RS



GIVEN:
RS-
Structures

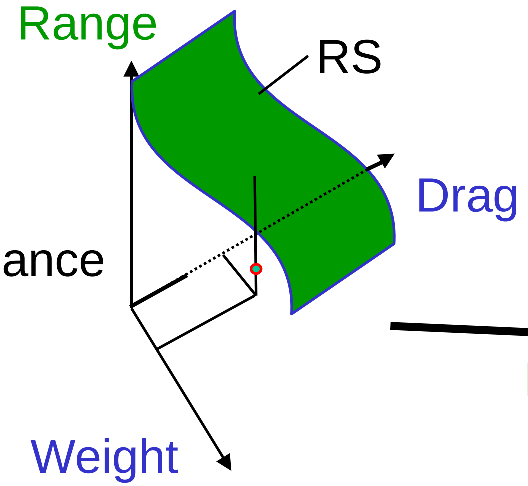


GIVEN:
RS-
Aerodynamics

Weight

Fast read-out from RS

Drag



GIVEN:
RS-
Performance

Range

System optimizer does this

FIND: geometry “a”, P, D., c1, c2
MAXIMIZE: R = RS(a,D.,P.,c_s,c_a)
SATISFY: P(a, Displac.) = Displac.(a, P)

System-level Optimization

System optimizer

proposes **geometry “a” , P, D., c1, c2**

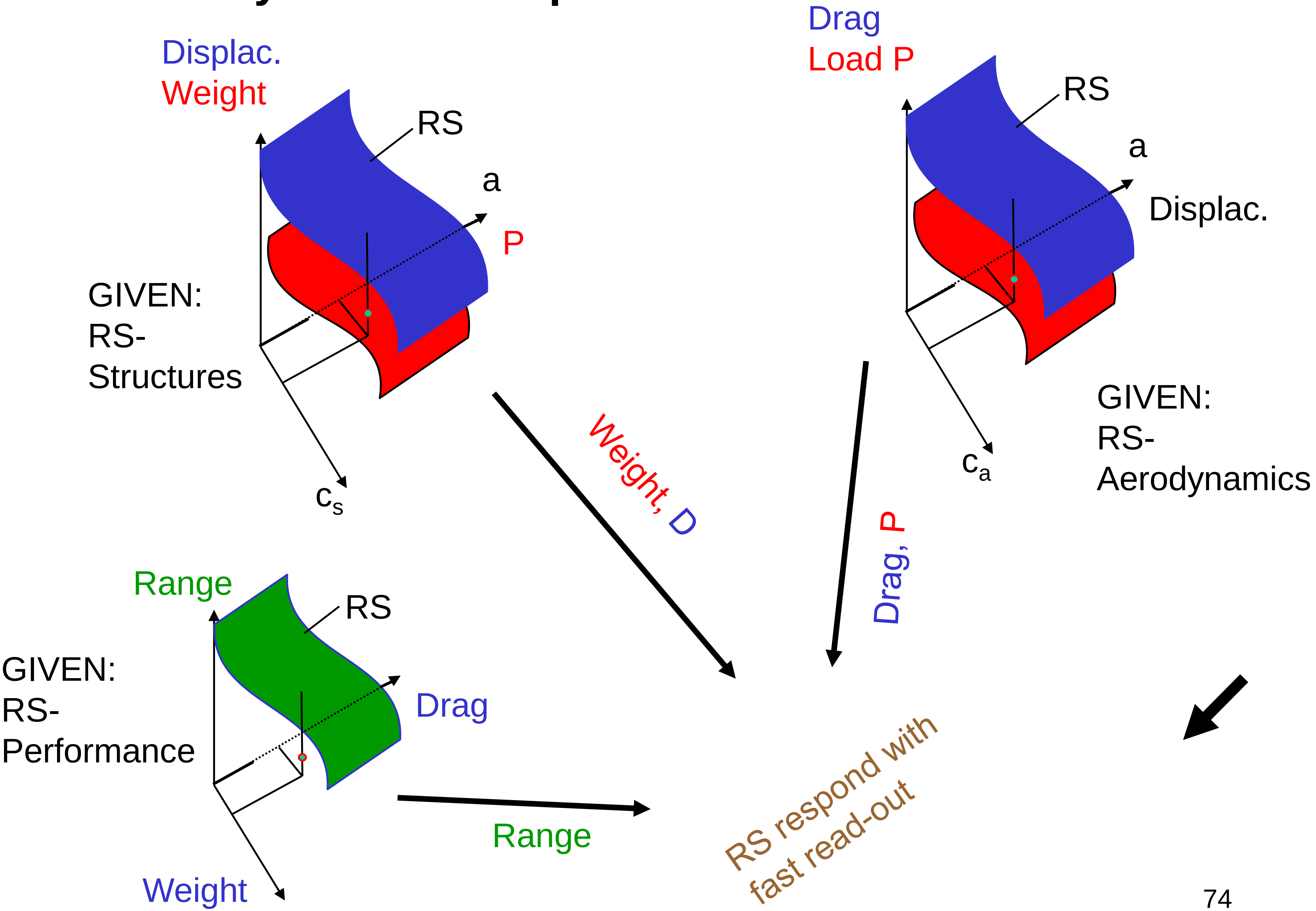
requests **$R = RS(a,D,P,c_s,c_a)$**

$P(a, Displac.) = Displac.(a, P)$

System optimizer does this

FIND: geometry “a”, P, D., c1, c2
MAXIMIZE: $R = RS(a,D.,P.,c_s,c_a)$
SATISFY: $P(a, Displac.) = Displac.(a, P)$

System-level Optimization



GIVEN:
RS-
Structures

GIVEN:
RS-
Aerodynamics

GIVEN:
RS-
Performance

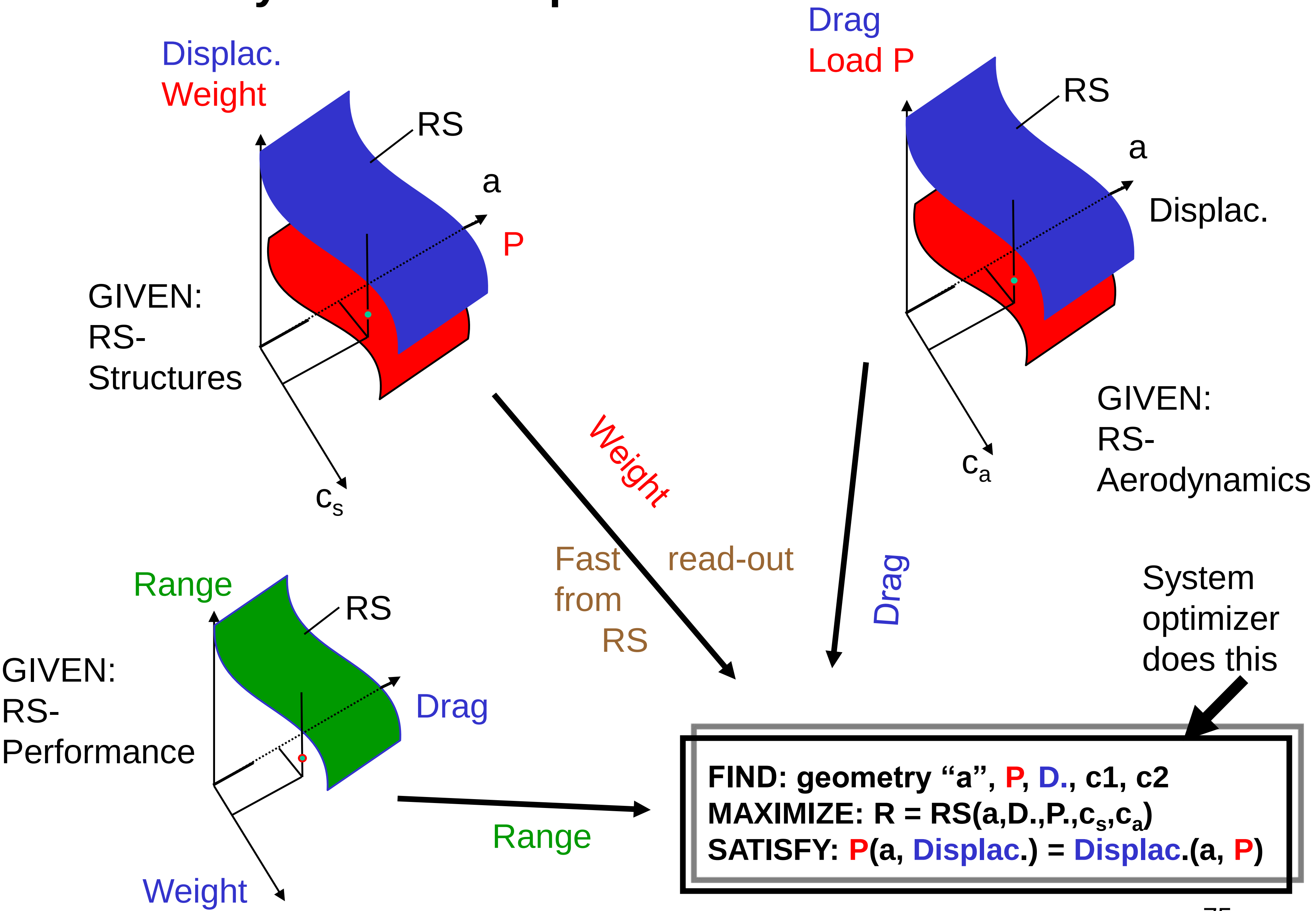
Weight, D

Drag, P

Range

RS respond with
fast read-out

System-level Optimization



GIVEN:
RS-
Structures

GIVEN:
RS-
Aerodynamics

GIVEN:
RS-
Performance

Fast read-out from RS

System optimizer does this

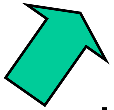
FIND: geometry “a”, P, D., c1, c2
MAXIMIZE: R = RS(a,D.,P.,c_s,c_a)
SATISFY: P(a, Displac.) = Displac.(a, P)

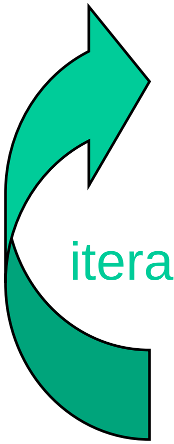
BLISS Formulation Contrasted with All-in-One Formulation

•Original problem, **All-in-One** *Find Design Variables V*
Minimize F(V)
Satisfy g(V) <= 0

• BLISS: **Decomposed** into two levels: V = { Xshared | Xlocal}

• Discipline or subsystem level *Given Xshared & Y coupling var.*
Find Local Design Variables Xloc
Minimize f(Xsh, Y, Xloc)
Satisfy g(Xsh, Y, Xloc) <= 0

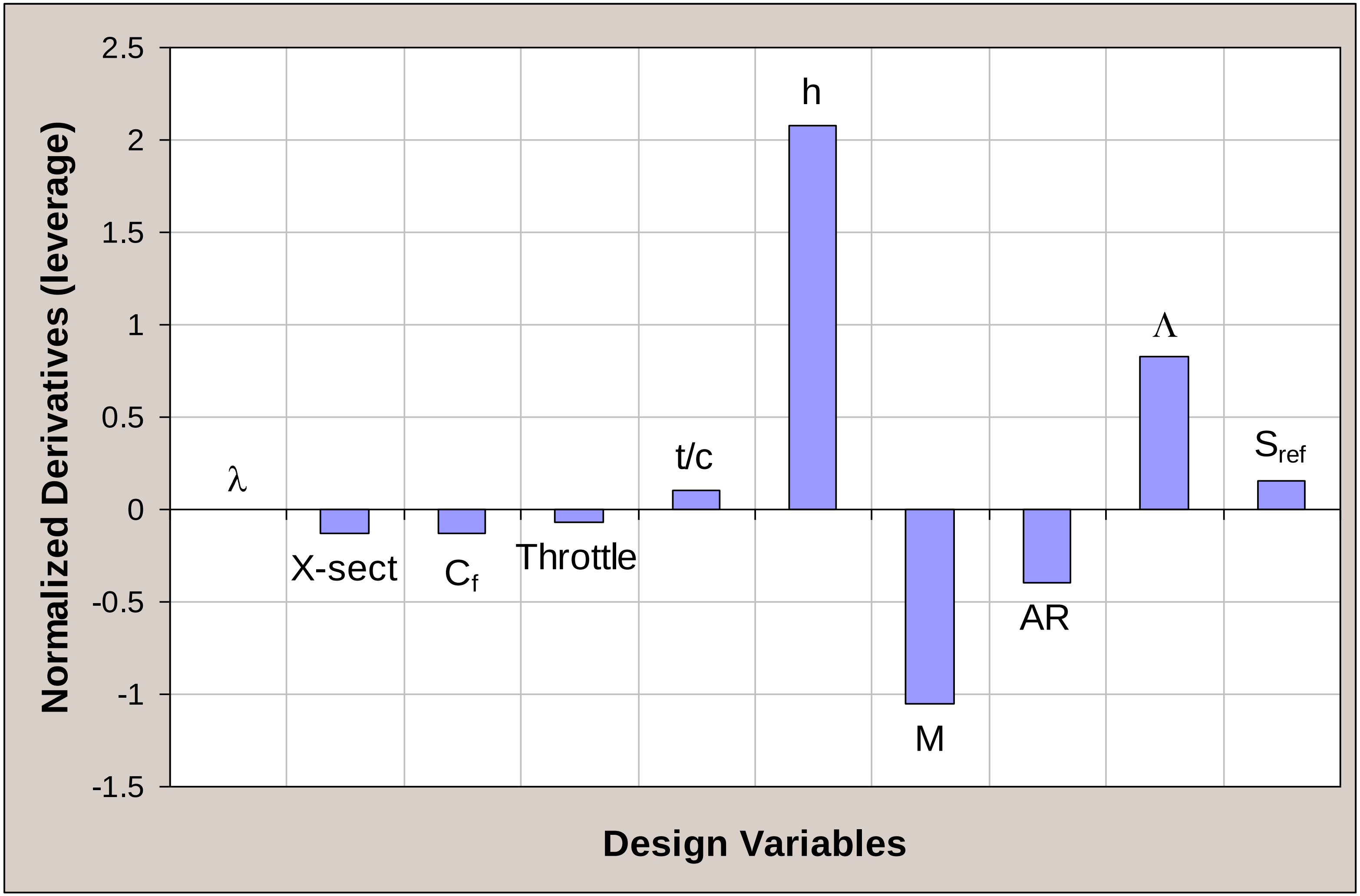


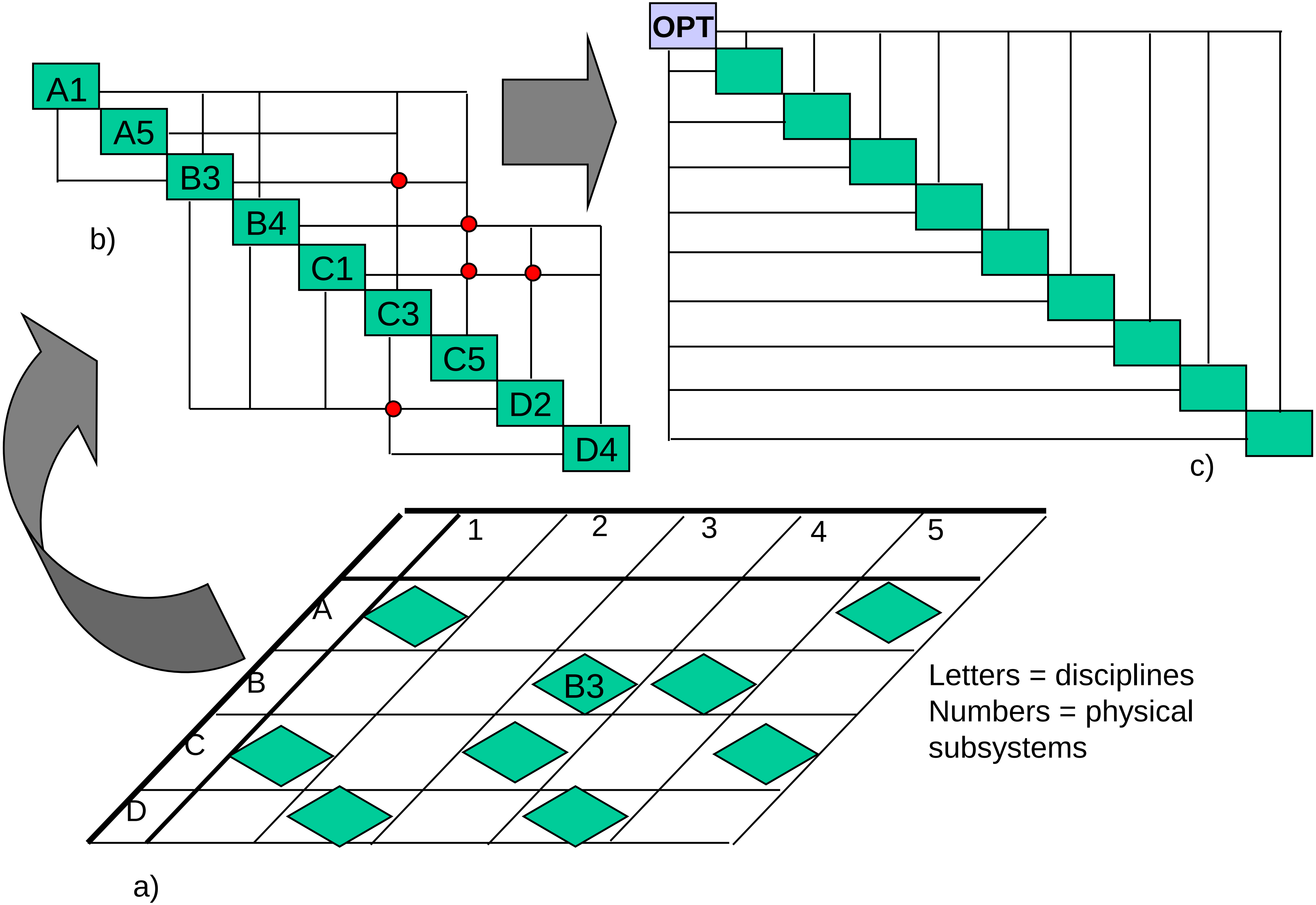


Many of these done **simultaneously**

• System level: *Given Optimum found in each module*
Find Xshared
Minimize F(Xshared)
Satisfy coupling constraints on Y

Results: Sensitivity Of Range to Variables





Letters = disciplines
Numbers = physical subsystems

Figure 1 BLISS supporting a project matrix organization

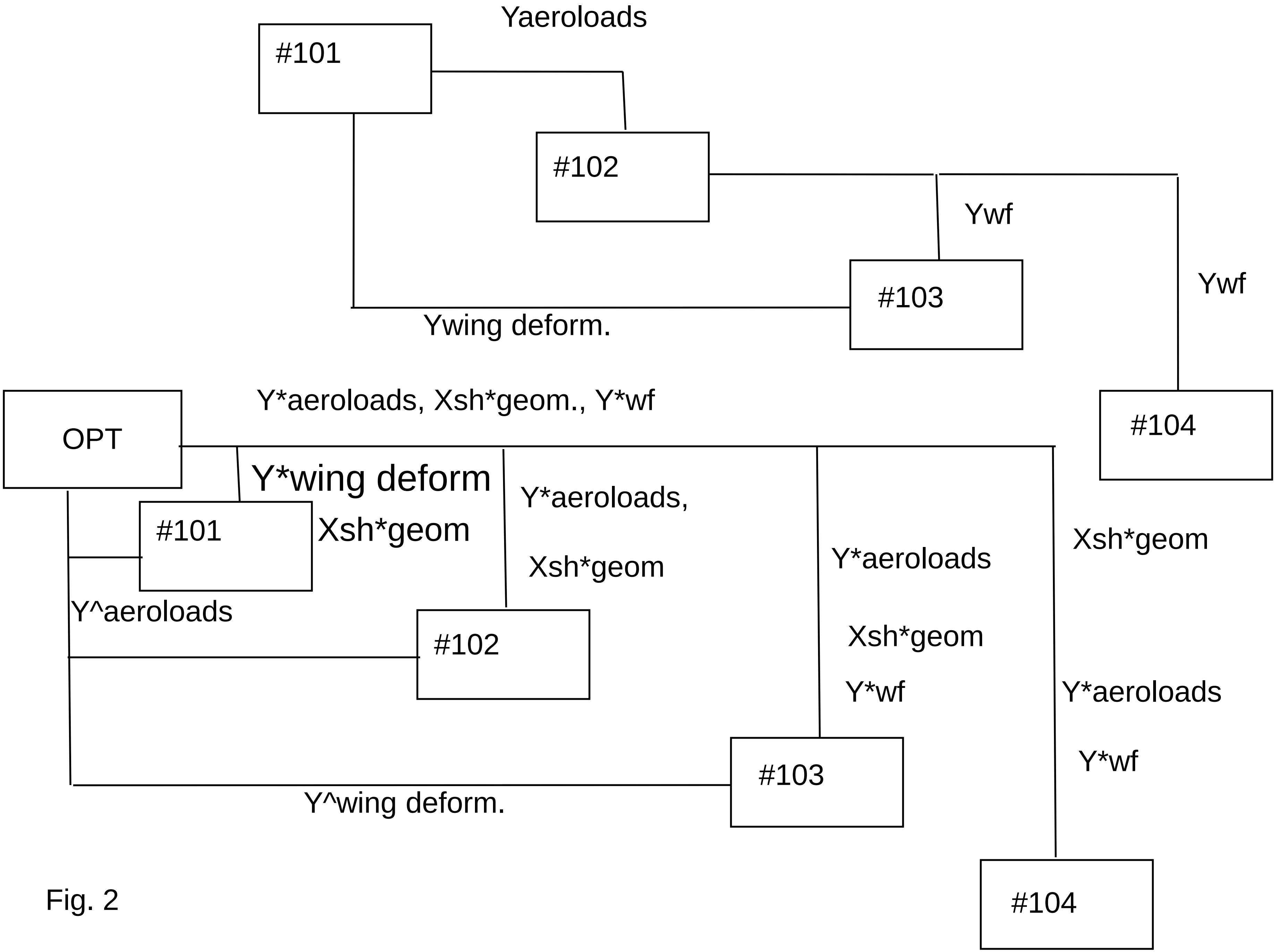
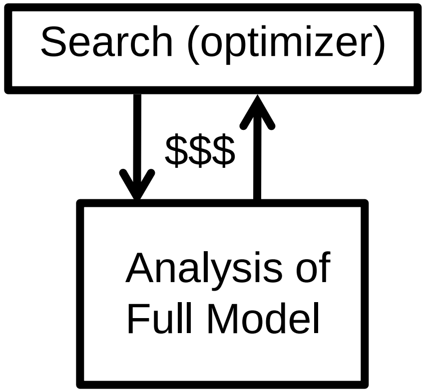

Yaeroloads
#101
#102
Ywf
#103
Ywf
Ywing deform.
#104
Y*aeroloads, Xsh*geom., Y*wf
OPT
Y*wing deform
#101
Xsh*geom
Y*aeroloads,
Xsh*geom
Y*aeroloads
Xsh*geom
Xsh*geom
Y*wf
Y*aeroloads
Y*wf
Y^aeroloads
#102
#103
Y^wing deform.
#104

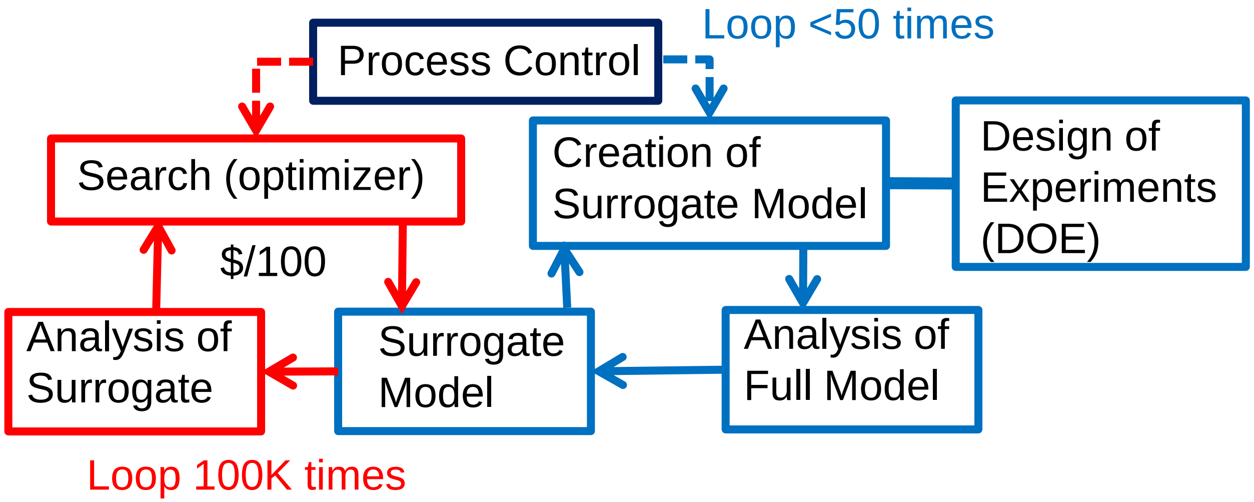
Fig. 2

Optimization Migrating from Structures to Other Disciplines

- Aerodynamics, Thermodynamics, Electromagnetic radiation, and more
- It became fundamental enabler in Composite materials
- It has always been the workhorse in space probe trajectory design
- Variety of techniques for decomposition of large problems into more manageable smaller ones have been developed
- **Search and Analysis decoupled via Approximations (Surrogate Models)**

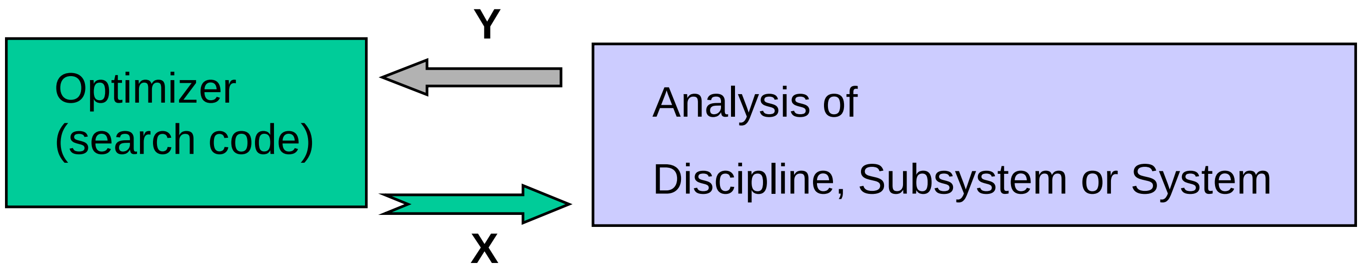


When model is inexpensive to analyze



Current practice in optimization applied to models expensive to analyze.

How to find optimal design despite curse of dimensionality



Y

Optimizer
(search code)

Analysis of

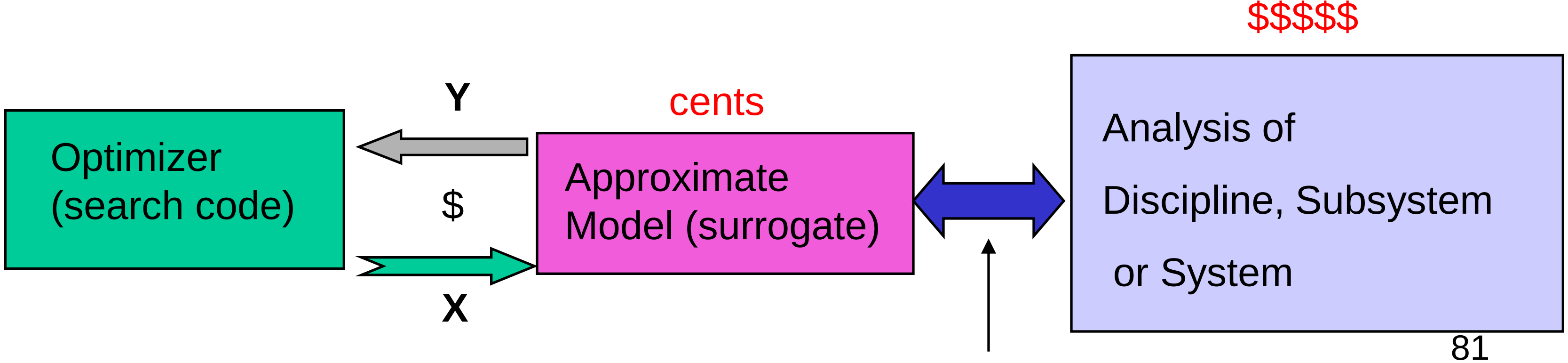
Discipline, Subsystem or System

X

- Curse of dimensionality: number of calls to analysis goes up exponentially with the number of design variables in X; **Not practical for large problems**.

Decouple Search from Analysis by use of Approximate Model

- Efficient search techniques
- Using approximate models (surrogates) to answer optimizer calls
- Approximation and Model Management in Optimization (AMMO)
- Exploiting massively concurrent processing



$$$$$

Y

cents

Optimizer
(search code)

$

Approximate
Model (surrogate)

Analysis of

Discipline, Subsystem

or System

X

- 10 to 50 times regardless of dim(X)

ESD.77 / 16.888 Multidisciplinary System Design Optimization

Spring 2010