INFORMS ANNUAL MEETING 2011

Charlotte, North Carolina

CPMS Daniel H. Wagner Prize Competition

Product Line Design and Scheduling at Intel

Evan Rash and Karl Kempf

Decision Engineering Group

Intel Corporation

Agenda

1. Business Background
2. The Strategic Business Problem
3. Mathematical Formulation
4. Our New Solution
5. Our Custom Implementation
6. Growing Business Impact


Two Found New Firm

MOUNTAIN VIEW — Two founders of Fairchild Semicon- ductor Division signed last mon lished a new in electronics com The firm, leased part of Middlefield R pied by Unior integrated cir of the firm' moved to San Founders Drs. Robe Gordon among eigh child Semic than 10 ye build it in producer They quit las

Bob Noyce (co-inventor of the integrated circuit)
Gordon Moore (author of "Moore's Law)

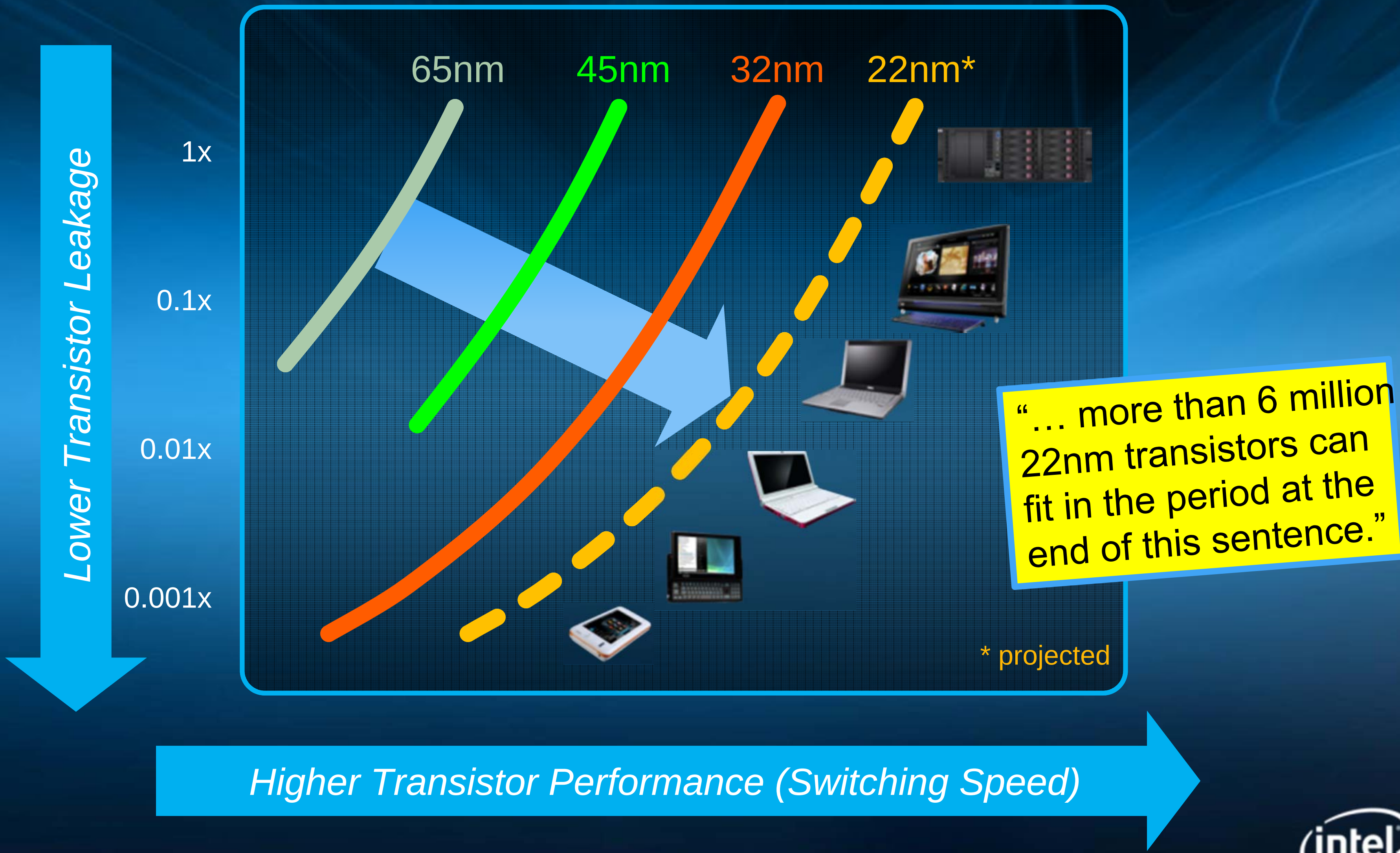
Founded
July 18th, 1968

intel

43 YEARS
of
Changing
The World

intel

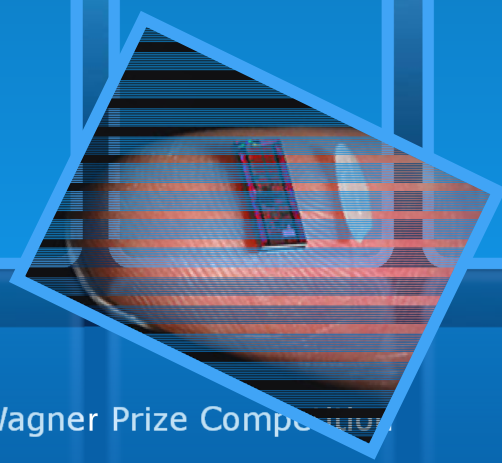
Leading Edge Process Technology



Leading Edge Product Technology

DATA CENTER	PC CLIENT	ULTRA MOBILITY	EMBEDDED & COMMS	DIGITAL HOME

- 2 Billion transistors/core
- 4 cores/chip



Feature, Market, and Time Dynamics

Different Markets Need a Different Mix of Features

Market1	$13	240,000
Market2	$15	300,000
Market3	$14	450,000
Market4	$12	880,000
Market5	$ 9	900,000
Marketing	**ASP**	**Vol**

Selling the product in the market brings in revenue

Different Markets Need a Different Mix of Features

Engineering and manufacturing incurs costs

Feature1	Feature2	Feature3	Feature4	Feature5	Feature6	Eng & Mfg
$ 300,000	$ 400,000	$ 400,000	$ 250,000	$ 300,000	$ 200,000	**Eng Cost**
$ 1.50	$ 0.35	$ 1.25	$ 0.50	$ 0.50	$ 0.25	**Mfg Cost / u**

Market1	$13	240,000
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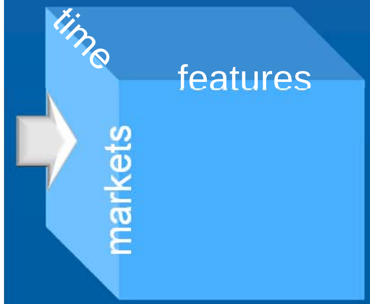
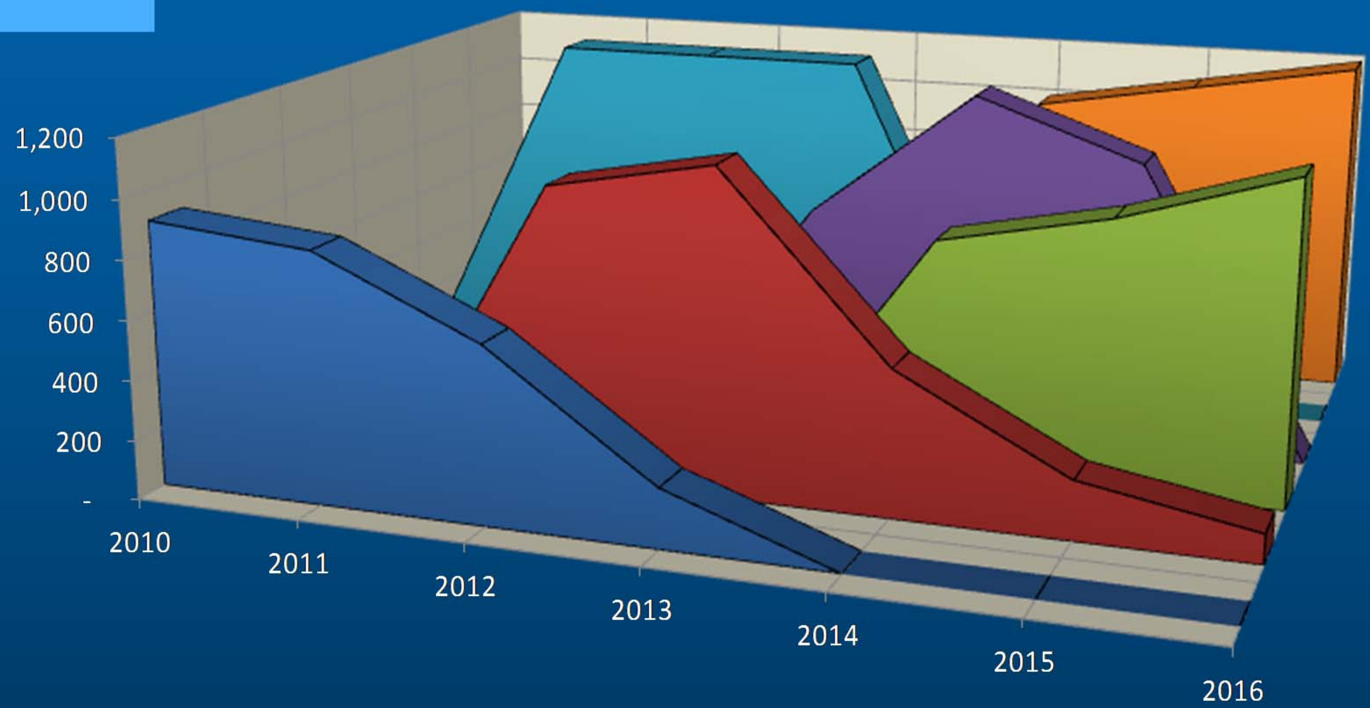
			$ 1.50	$ 0.35	$ 1.25	$ 0.50	$ 0.50	$ 0.25	Mfg Cost / u
Market1	$13	240,000	1	0	0	1	0	1	
Market2	$15	300,000	1	0	0	0	1	1	
Market3	$14	450,000	1	1	2	0	0	0	
Market4	$12	880,000	2	0	1	0	0	0	
Market5	$ 9	900,000	1	3	0	0	0	0	
Marketing	ASP	Vol							

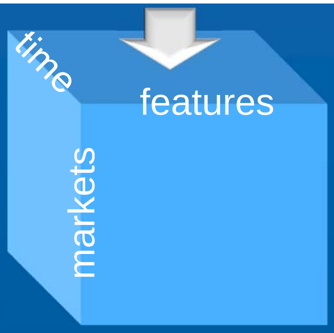
Markets have unique feature requirements



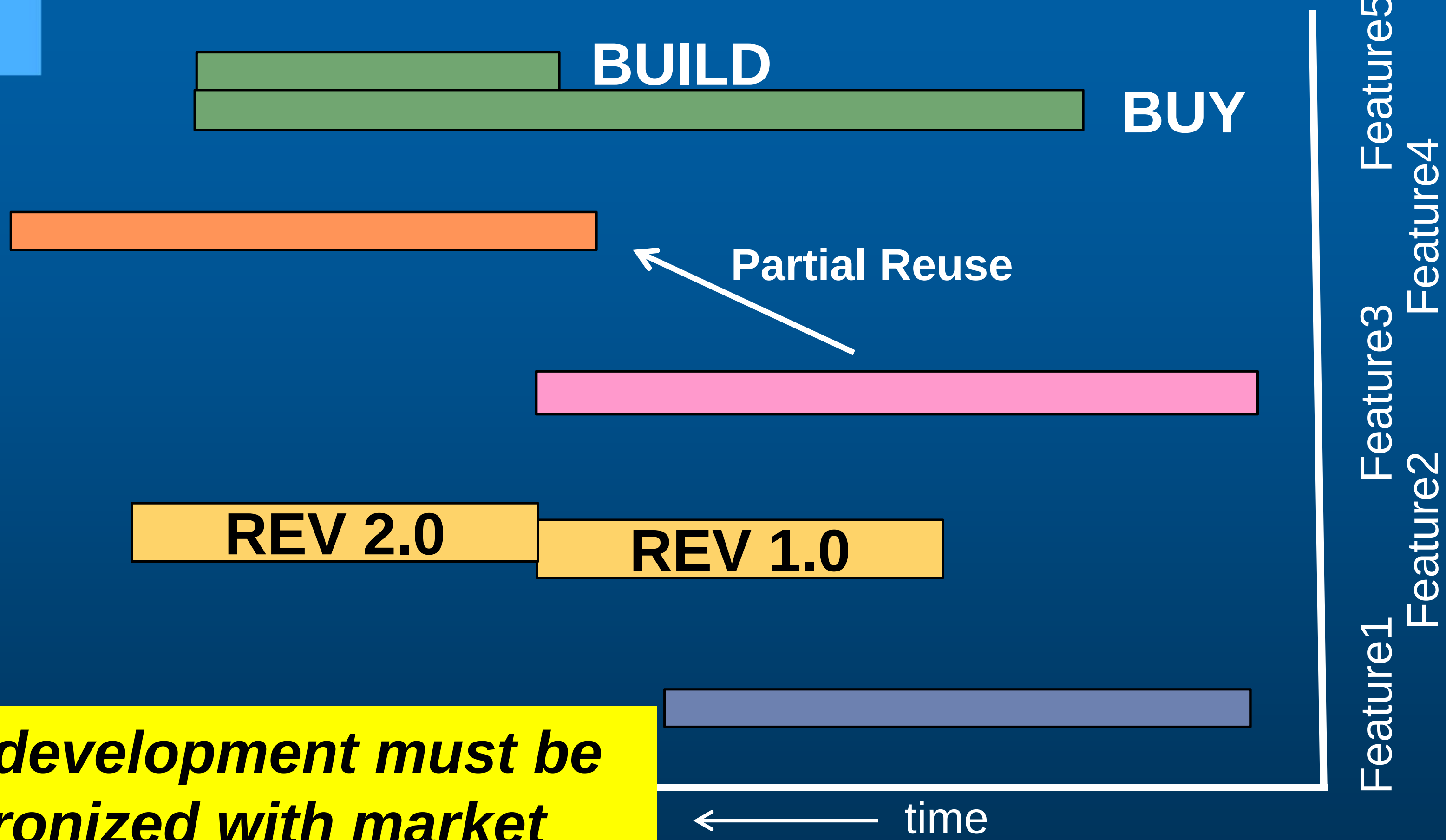
Different Markets Have Different Timings



Markets are not all synchronized in time



Different Features Have Different Availabilities



Feature development must be synchronized with market windows

Constraints

- **Feature sets in the products must meet (or exceed) the needs of the target markets**

- **Features must be engineered in time to be integrated into the products**
- **Products must be engineered and manufactured to hit the market timings**

- **The engineering budget is finite (leading to an emphasis on reuse)**

Objective

- **Maximize Profit** ***(Max Revenue, Min Eng and Mfg Cost)***

Business questions include (at least):

- **Given an engineering budget, what set of products maximize revenue or profit?**
- **Given a revenue target, what set of products minimize cost, with what engineering budget?**
- **Given a number of Features to engineer, what is the profit maximizing order of development?**
- **Given a Feature 'build vs. buy' decision (cost, timing), which generates the most profit?**

Difficult to solve with standard techniques due to many different constraints, competing objectives, and interrelated tradeoffs

Math

Define Problem & Formulate as Mathematical Programming

Show Complexity & Difficulties involved with Traditional techniques

Solution Methodology & Implementation

The Core Problem

Generate a Product Line ***Strategic***

Map products into markets

Schedule product development

Generate Product Features ***Tactical***

Meet or exceed market requirements

Schedule feature development

Optimize for Profitability ***Strategic***

Product line must optimize profitability

Must consider engineering budgets

Generating the Product Line

Inputs

Set of markets $\{1,\ldots,M\}$

Number of products *At most one product per market* $P \leq M$

Time horizon $\{1,\ldots,T_0,\ldots,T\}$

Decisions

How many products to build β_p *Binary*

When to introduce products $z_p \in \{T_0,\ldots,T\}$ *Integer*

Which markets to sell products into? α_{pmt} *Binary*

Generating Product Features

Inputs

Set of features $\{1,\ldots,F\}$

Market Requirements D_{mf}

Decisions

Product Features *Units of Feature f in Product p* x_{pf} *Integer*

Feature Availability $y_f \in \{T_0,\ldots,T\}$ *Integer*

Optimize for Profitability

Inputs

- **Market Volumes and Prices** v_{mt}, p_{mt}
- **Feature Engineering Cost (with Reuse)** $R_f(t)$
- **Product Engineering Cost** A
- **Feature Mfg. Cost** c_f

Expressions

- **Revenue**

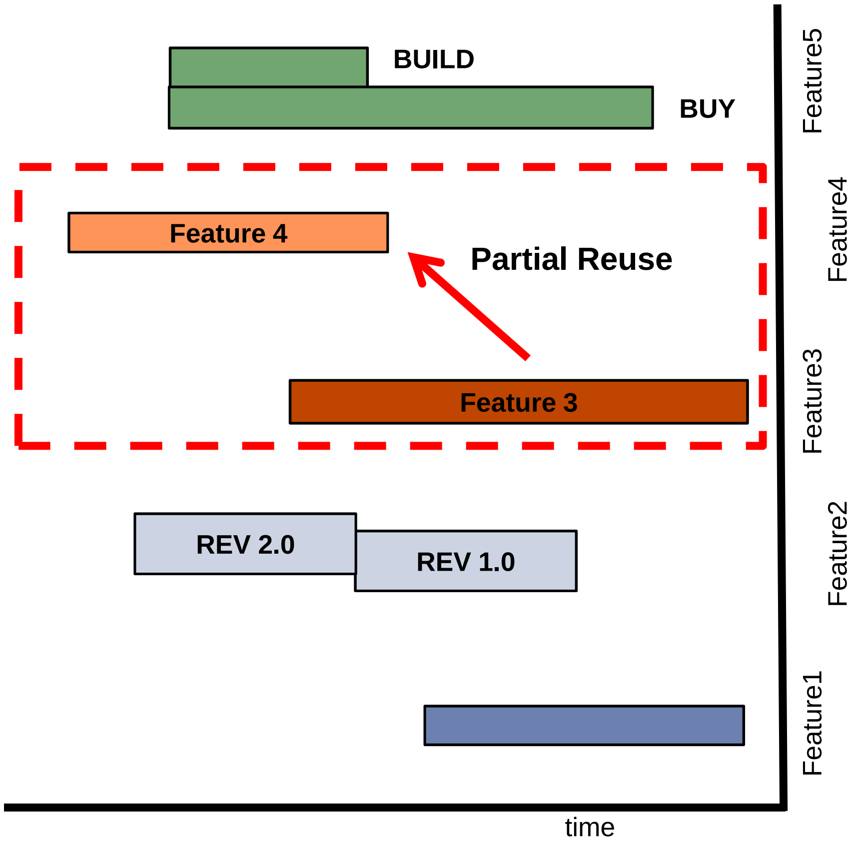
$$\sum_{p=0}^{P} \sum_{m=0}^{M} \sum_{t=0}^{T} \alpha_{pmt} v_{mt} \left(p_{mt} - \sum_{f=0}^{F} c_f x_{pf} \right)$$

- **Engineering Cost**

$$A \sum_{p=0}^{P} \beta_p + \sum_{f=0}^{F} \sum_{t=0}^{T} R_f(t)$$

Reuse Function

- Engineering features presents **reuse** opportunities
  - Developing **Feature 3** **<u>may</u>** cause developing Feature 4 to be cheaper/faster
- The **Reuse Function** defines these reuse synergies
  - Typically dynamic and complex



Reuse Function Example

A hypothetical Reuse Function where developing one feature in a group causes subsequent feature development to be 50% cheaper

Feature f	Group $G(f)$	$R_f(t)$ when $t-1=y_f$
1	1	1
2	2	.5 if $y_2 > y_3$, else 1
3	2	.5 if $y_3 > y_2$, else 1
4	3	.5 if $y_4 > y_5$, else 1
5	3	.5 if $y_5 > y_4$, else 1

$$R_f(t) = \begin{cases} 1 \text{ if } & y_f = \min_{g \in G(f)} y_f \\ .5 \text{ if } & \exists g \in G(f) \mid y_g < y_f \end{cases}$$

Full Formulation

Objective: Maximize Profit

$$\max \sum_{p=0}^{P} \sum_{m=0}^{M} \sum_{t=0}^{T} \alpha_{pmt} V_{mt} \left(P_{mt} - \sum_{f=0}^{F} C_f x_{pf} \right) - \sum_{f=0}^{F} \sum_{t=0}^{\mathrm{T}} R_f(t) - A \sum_{p=0}^{P} \beta_p$$

Subject to:

$\sum_{p=0}^{P} \alpha_{pmt} \leq 1 \quad \forall m, t$	One Product per Market
$D_{mf}\, \alpha_{pmt} \leq x_{pf} \quad \forall p, m, t$	Market Satisfaction Constraint
$z_p \geq \max\{f: \beta_p > 0 \mid y_f\}$	Product Availability Constraint
$\alpha_{pmt} = 0 \quad \forall p, m, t < z_p$	Market Coverage Availability Constraint
$MT\beta_p \geq \sum_{m=0}^{M} \sum_{t=0}^{T} \alpha_{pmt}$	Product Selling Requirement
$\sum_{f=0}^{F} R_f(t) \leq S_t$	Resource Constraint
$\beta_p \in \{0,1\}$	Binary Constraint
$\alpha_{pmt} \in \{0,1\}$	Binary Constraint
$x_{pf} \in \{0, \ldots, \max D_{mf}\}$	Integral Units of Features Constraint
$y_f \in \{T_0, \ldots, T + \Pi\}$	Scheduling Window Constraint
$z_p \in \{T_0, \ldots, T + \Pi\}$	Scheduling Window Constraint

Why Is This a Hard Problem?

Non-linearity

- Reuse Function
- Objective Function & Constraints

Integral & Binary Decisions

- Scheduling
- Mapping

Combinatorics & Problem Size

Difficult to solve by traditional techniques!

- ***Linear/Mixed-Integer Programming***
- ***Constraint Programming***

Our Solution

- Integrate diverse OR techniques
  - Resource-Constrained Job Scheduling
  - Optimal Set Covering
  - Portfolio Optimization
  - Dynamic Programming
- Decompose Problem into Multiple Stages
  - Outer “strategic” Genetic Algorithm
  - Inner “tactical” Heuristics and MIPs
  - Financial Optimization through Genetic Algorithm Fitness

Decomposition – Product Line Design

Outer Genetic Algorithm

1. Product Release Schedule
2. Product to Market Mappings
6. Resource Constraints
7. Financial Objectives

Inner Set Covering / Heuristics

3. Product Features
   Ext: Feature Substitutions
4. Feature Schedules
5. Feature Reuse

Decomposition – Generate Product Features

Outer Genetic Algorithm

1. Product Release Schedule
2. Product to Market Mappings

Per Product →

Inner MIPs and Heuristics

3. Product Features
   Ext: Feature Substitutions
4. Feature Schedules
5. Feature Reuse

← Per Product

6. Resource Constraints
7. Financial Objectives

Decomposition – Financial Optimization

Outer Genetic Algorithm

Mutation & Crossover

1. Product Release Schedule

Per Product

2. Product to Market Mappings

Selection

6. Resource Constraints

7. Financial Objectives

Strategic

Inner Set Covering / Heuristics

3. Product Features
   Ext: Feature Substitutions

4. Feature Schedules

5. Feature Reuse

Per Product

Tactical

Outer “Strategic” Algorithm

1. **Outer: Creating Product Schedules**

   Generate a random chronologically sorted product schedule, with some products “turned off”.

   Use crossover to “zip” different schedules together and mutations to randomly permute schedule by pushing products out and pulling products in

2. **Outer: Creating Market to Product Mappings**

   For each market randomly cover or skip the market. If covered, select a random product from the list generated in 1

Inner "Tactical" Algorithm

3. Inner: Determine Product Features (MIPs)

- Cover market requirements with minimum manufacturing cost
- Cover market requirements with minimum engineering cost

Randomly alternate and allow the evolutionary process to pick the best

4. Inner: Deduce Feature Schedules

Back out the feature engineering schedule based on when the features need to be available for the product's availability (1)

5. Inner: Evaluate Reuse

Evaluate the reuse of the feature schedule from (4)

Outer "Strategic" Algorithm

6. **Evaluate Resource Constraint**

   Evaluate the engineering resources for the entire roadmap

   Model engineering resource constraints as soft constraints

   Use a Lagrangian penalty approach similar to the concept of an "overtime" cost of exceeding the available engineering resource supply

7. **Evaluate NPV & Fitness**

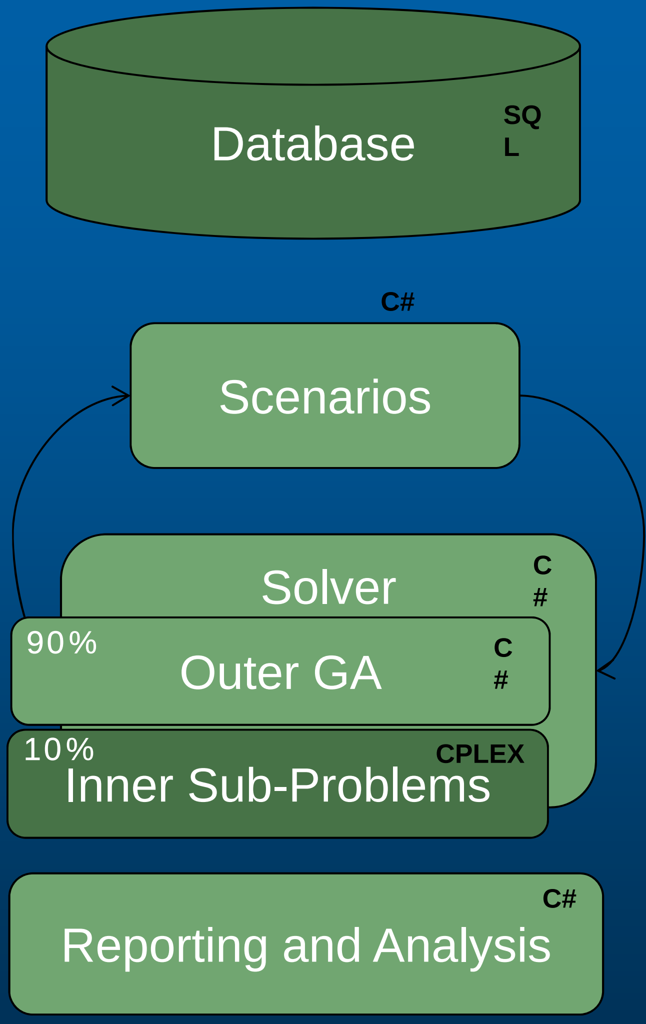
   Evaluate the fitness of the product line by determining its NPV and subtracting out any resource overage penalties

“Pinning” Parts of the Solution

- Planning involves many strategic aspects
  - Not always possible to solve with a “clean slate”
- Solver must be able to “pin” portions of the solution in place and solve using remaining degrees of freedom
- Examples
  - Locking products onto the roadmap
  - Locking feature availability schedules
  - Forcing entry into particular markets

Implementation

- Custom Implementation (C# .NET)
  - Required Custom Mutation/Crossover and Solution Flow
- Inner sub-problem solved via modular heuristics plugged into larger GA
  - Most Heuristics: C#
  - Feature Substitution: OPL CPLEX



The Business Process

BEFORE

1) Many spreadsheets with local databases

2) Local view by product, sometimes by division

3) Few what-ifs

AFTER

1) One tool with global database (HW and SW)

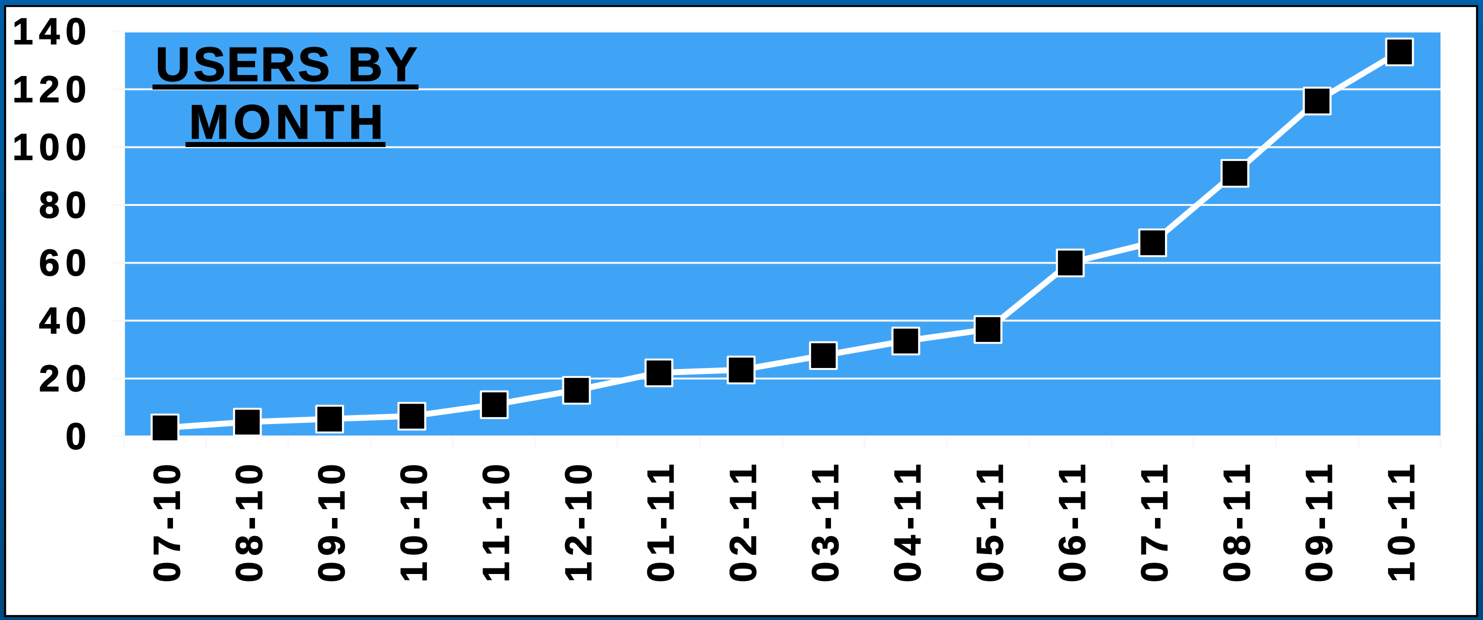
2) Holistic view across divisions and products

3) Many what-ifs

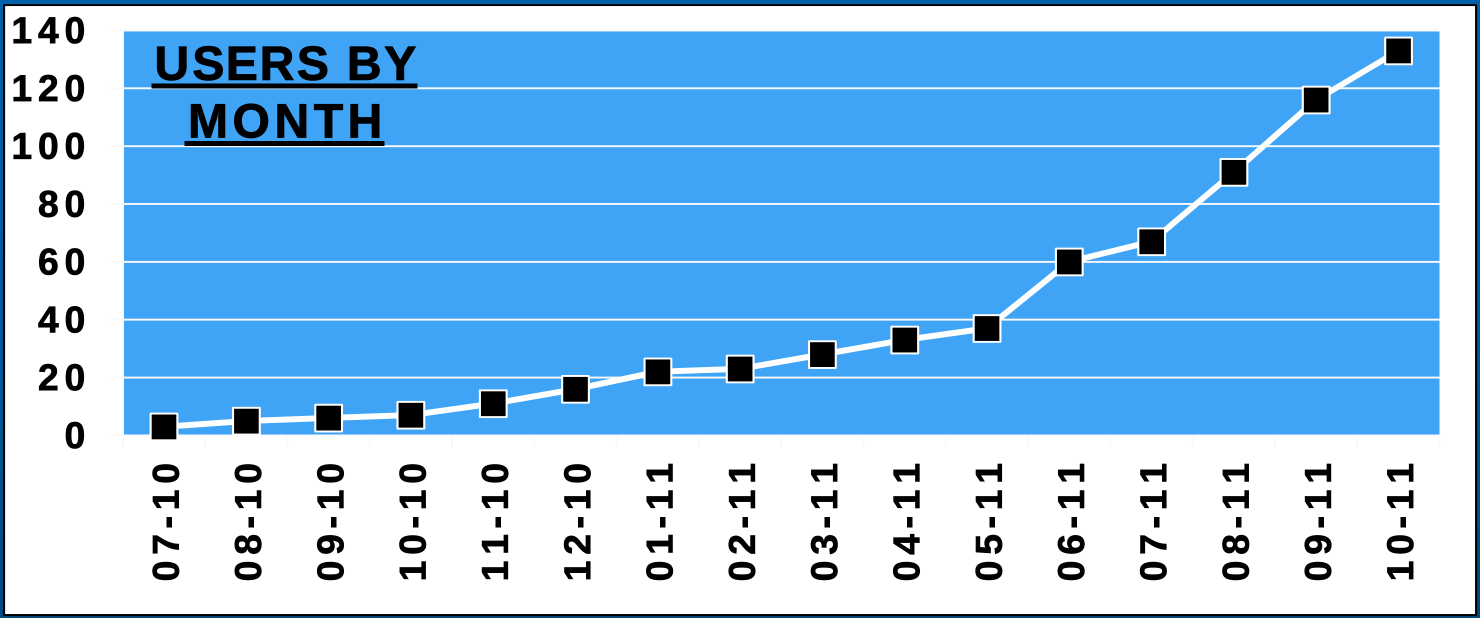
The Business Process

BEFORE	AFTER
1) Many spreadsheets with local databases	1) One tool with global database (HW and SW)
2) Local view by product, sometimes by division	2) Holistic view across divisions and products
3) Few what-ifs	3) Many what-ifs
4) Difficult decision making between finance, planning, and engineering (design and mfg)	4) Collaborative decision making between all of the product functions
5) No global optimization and little (if any) local optimization	5) Global profit optimization
6) Little reuse between divisions and within divisions	6) Increasing reuse across divs and products (few%/mo)

User Data and Feedback



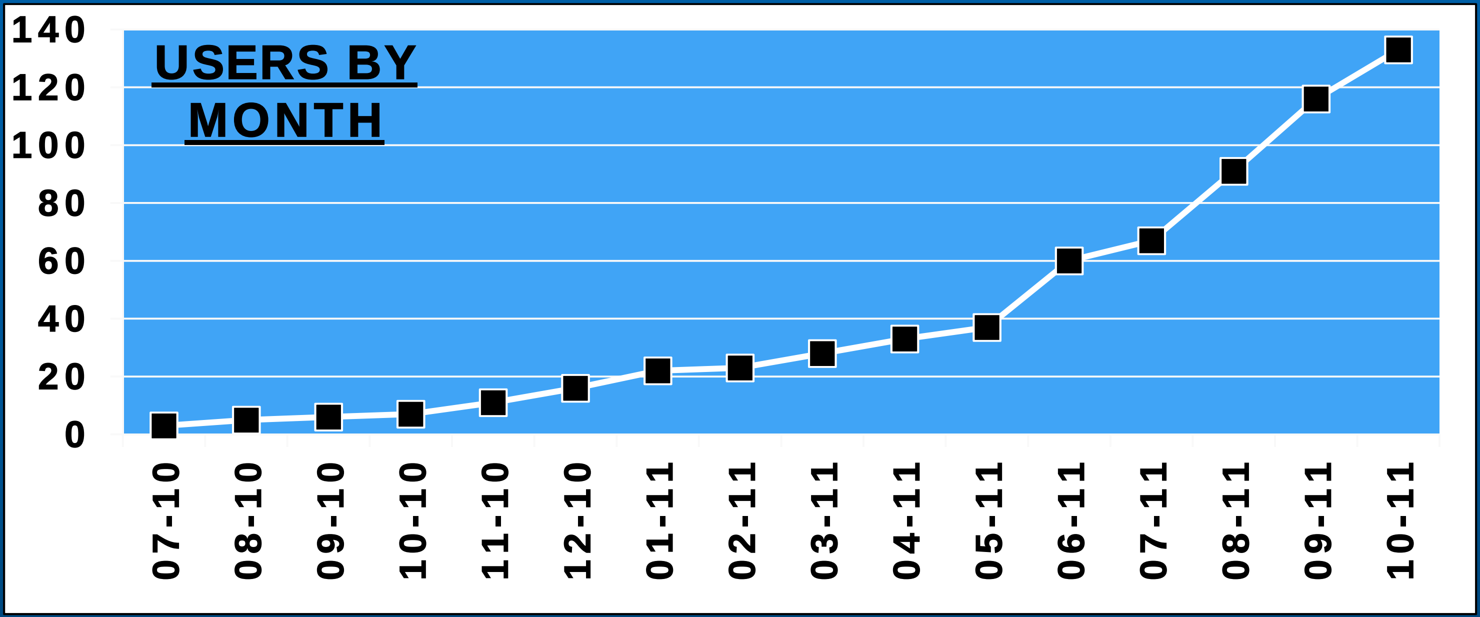
User Data and Feedback



JOB TITLE	# USERS	HRS USED
STRATEGIC PLANNERS	16	996
PROJECT/PROGRAM MANAGER	39	476
PRODUCT DESIGN ENGINEER	23	394
FINANCIAL ANALYST	39	342
PRODUCT MARKETING ENGINEER	5	63
OPERATION MANAGER	3	21
PRODUCT SOFTWARE ENGINEER	8	4
TOTAL	133	2296

PRODUCT DIVISION	# OF USERS
Div-1	58
Div-2	25
Div-3	12
Div-4	11
Div-5	9
Div-6	4
Div-7	3
Div-8	3
Div-9	2
Div-Admin	3
Misc	3
TOTAL	133

User Data and Feedback



"No idea how we can optimize market coverage without a tool like this."

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TOTAL	133

"We are finally working in a transparent system instead of spreadsheets on random shared drives."

"Useful as an acumen tool as well as learning about where synergies exist for our products."

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Conclusion

- This is a complex problem considering market, feature, and product time dynamics
- Extremely difficult to solve with traditional techniques
- Developed and implemented a custom solution to the problem
- The system currently has users across divisions and job roles
- We believe the system (over time) will become crucial to Intel's continuing success


WHAT WE MAKE.
IT'S WHAT WE MAKE POSSIBLE.
intel
Corporate Overview

Extensions

- Feature Substitution
  - Feature A or Feature B can be interchanged
- Time to Market Penalties
  - Late products suffer in the marketplace
- Minimum vs. Target Market Requirements
  - Feature A is a must-have, Feature B is a value-add
- Build vs. Buy decisions
  - Develop in house or license?
- NPV Optimization