This article was the basis for the series that is appearing in the May, June, and July2005 issues of Chemical Engineering Progress, the flagship publication of the American Institute of Chemical Engineers.

40 Inventive Principles with Examples for Chemical Engineering

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Principle 1. Segmentation

A. Divide an object into independent parts.
   - *The concept and use of independent unit operations in chemical engineering*
   - *The use of different components of a unit operation to allow variable processing as a function of reactants and products desired*
   - *Separate reaction steps and conditions according to kinetic rates*
   - *Separate pipeline transport of fluids via inert fluid segments*

B. Make an object easy to disassemble.
   - *Quick disconnect joints in piping systems*
   - *Plate and frame heat exchangers*

C. Increase the degree of fragmentation or segmentation. .
   - *Multiple sized semi-plant operating equipment to accommodate variability in demand and requirements*
   - *Baffles in tanks, reactors, and heat exchangers*

Principle 2. Taking out

A. Separate an interfering part or property from an object, or single out the only necessary part (or property) of an object.
   - *Locate a noisy compressor outside the building where compressed air is used.*
   - *Use fiber optics or a light pipe to separate the hot light source from the location where light is needed.*
   - *Locate hazardous or flammable chemical operations in separate facilities with remote monitoring and alarms*
   - *Separate reactive chemical storage from primary warehouse or raw material storage*
   - *Eliminate a hazardous chemical reaction step with alternative chemistry*

Principle 3. Local quality

A. Change an object's structure from uniform to non-uniform, change an external environment (or external influence) from uniform to non-uniform.

- *Use a temperature, density, reaction, or pressure gradient instead of constant temperature, density or pressure within a unit operation*
- *Vary external environmental conditions around a particular unit operation*
- *Static mixer designs*
- *Flow measurements based on pressure reduction (orifice, venture)*

B. Make each part of an object function in conditions most suitable for its operation.
- *Vary the internal design of a distillation column to reflect varying flows and fluid characteristics*
- *Vary the mixing within a vessel to deliberately produce non-uniform product quality*
- *Vary reactor operating conditions with kinetic rates and rate constants*
- *Vary internals of a screw conveyor to process or material conditions*
- *Individual control units vs. overall system control*

C. Make each part of an object fulfill a different and useful function.
- *Use a separation device to do both filtration and washing*
- *Separation column that enriches, rectifies, and also serves as a reactor*
- *Piping system that both transports and mixes via inclusion of internal mixing devices*

Principle 4. Asymmetry

A. A. Change the shape of an object from symmetrical to asymmetrical.
- *Asymmetrical mixing vessels or asymmetrical vanes in symmetrical vessels improve mixing (cement trucks, cake mixers, blenders).*
- *Make hopper discharge asymmetric to minimize hold up increase flow capability*

B. If an object is asymmetrical, increase its degree of asymmetry.
- *Change from circular O-rings to oval cross-section to specialized shapes to improve sealing.*
- *Use astigmatic optics to merge colors for process indicators*
- *Lobe pumps*

Principle 5. Merging

A. Bring closer together (or merge) identical or similar objects, assemble identical or similar parts to perform parallel operations.
- *Personal computers in a network*
- *Automated tank and blending systems*
- *Reactive distillation systems and columns*
- *Vanes in a ventilation system*
- *Electronic chips mounted on both sides of a circuit board or subassembly*

B. Make operations contiguous or parallel; bring them together in time.
- *Medical diagnostic instruments that analyze multiple blood parameters simultaneously*
- *Continuous chemical processing*

- *Derivative process control*
- *Combine exothermic and endothermic heat transfer requirement*
- *Auto catalytic reactor*
- *Place raw material and process plants near each other to minimize shipping costs and transportation hazards*

Principle 6. Universality

A. Make a part or object perform multiple functions; eliminate the need for other parts.
   - *Reactive distillation column*
   - *A vaccum jet that both pumps and reduces pressure*
   - *An eduction system that mixes and pumps*
   - *Solids processing that both dries and changes surface chemistry*
   - *Vessels with multi-functional design that serve as reactors, separators, and extraction units*

Principle 7. "Nested doll"

A. Place one object inside another; place each object, in turn, inside the other.
   - *Nested control loops in control systems*
   - *Encapsulated, time release formulations*
   - *Emulsion systems*
   - *Static mixers within a piping system*
B. Make one part pass through a cavity in the other.
   - *Catalyst systems with designed pore structures*
   - *Membrane filtration systems*

Principle 8. Anti-weight

A. To compensate for the weight of an object, merge it with other objects that provide lift.
   - *Eductors*
   - *Use of stochiometry changes in a gas phase reaction to drive the reaction toward completion*
   - *Use tanks above ground to provide suction head for pumps*
B. To compensate for the weight of an object, make it interact with the environment (e.g. use aerodynamic, hydrodynamic, buoyancy and other forces).
   - *Aircraft wing shape reduces air density above the wing, increases density below wing, to create lift. (This also demonstrates Principle 4, Asymmetry.)*
   - *Pneumatic conveying systems*
   - *Vacuum jet*

Principle 9. Preliminary anti-action

A. If it will be necessary to do an action with both harmful and useful effects, this action should be replaced with anti-actions to control harmful effects.
    - *Buffer a solution to prevent harm from extremes of pH*
    - *Add an inhibitor to prevent undesired polymerization*
B. Create beforehand stresses in an object that will oppose known undesirable working stresses later on.
    - *Diluting a dangerous reactant below its reactive concentration prior to use*
    - *Adjust inhibitor levels as a function of time, temperature requirements of shipping*
    - *A safety system that operates inversely to unsafe operating conditions*

Principle 10. Preliminary action

A. Perform, before it is needed, the required change of an object (either fully or partially).
    - *Pre-pasted wall paper*
    - *Pre-load equipment operating instructions based on customer input and demand*
    - *Preloading of tanks for batch operations*
    - *Pre-heat or pre-cool a piece of operating equipment to shorten startup time*
B. Pre-arrange objects such that they can come into action from the most convenient place and without losing time for their delivery.
    - *Locate chemical manufacturing plant close to either supplier or customer*
    - *Flexible semi-commercial manufacturing cell*s
    - *Intermediate process raw material inventory systems*
    - *Raw material generation on-site*

Principle 11. Beforehand cushioning

A. Prepare emergency means beforehand to compensate for the relatively low reliability of an object.
    - *Magnetic strip on photographic film that directs the developer to compensate for poor exposure*
    - *Alternate air and other utility systems for use in emergencies*
    - *Provide means for emergency supply of cooling, heating, or pressure supply*
    - *Pre-load cooling elements*
    - *pH buffers*

Principle 12. Equipotentiality

A. In a potential field, limit position changes (e.g. change operating conditions to eliminate the need to raise or lower objects in a gravity field).
    - *Tank car design features that limit movement upon impact and shock*

- *Locks in a channel between 2 bodies of water*
- *Small storage units that bring raw materials to the right position in a batch chemical reaction*
- *Process designs that use multi-floor process buildings to take advantage of gravity flow*

Principle 13. 'The other way round'

A. Invert the action(s) used to solve the problem (e.g. instead of cooling an object, heat it)
   - *To loosen stuck parts, cool the inner part instead of heating the outer part.*
   - *Pre-coat a filter to improve its filtration capabilities*
   - *Change heating and cooling sides of a heat exchanger*

B. Make movable parts (or the external environment) fixed, and fixed parts movable).
   - *Use of static mixers within pipes as "fixed" mixers*
   - *Moving sidewalk with standing people*

C. Turn the object (or process) 'upside down'
   - *Turn an assembly upside down to insert fasteners (especially screws)*
   - *Empty grain from containers (ship or railroad) by inverting them*
   - *Invert the order of reactant addition*

Principle 14. Spheroidality - Curvature

A. Instead of using rectilinear parts, surfaces, or forms, use curvilinear ones; move from flat surfaces to spherical ones; from parts shaped as a cube (parallelepiped) to ball-shaped structures.
   - *Tower packing evolution from simple rings to convoluted saddle designs*

B. Use rollers, balls, spirals, domes.
   - *Curvilinear surfaces to increase pressure resistance to pressure*
   - *Ball point and roller point pens for smooth ink distribution*
   - *Grinding systems using rollers and balls vs. linear systems*

C. Go from linear to rotary motion, use centrifugal forces.
   - *Change from linear filtration to centrifugal separation devices*
   - *Rotating separation units*

Principle 15. Dynamics

A. Allow (or design) the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition.
   - *Process control based on variable input as to optimum set points*
   - *A variable speed pump*
   - *Adjustable settings on distillation columns, reactors, temperature control loops*
   - *Use of multiple skills of operators and skilled tradespeople*

B. Divide an object into parts capable of movement relative to each other.

- *Oldshue separation column*
- *Variable pitch screw conveyor*

C. If an object (or process) is rigid or inflexible, make it movable or adaptive.
   - *Variable speed pumps and conveyors*
   - *The flexible sigmoid scope, for medical examination*
   - *Process flows are directly in response to externally transmitted market or inventory conditions*

Principle 16. Partial or excessive actions

A. If 100 percent of an object is hard to achieve using a given solution method then, by using 'slightly less' or 'slightly more' of the same method, the problem may be considerably easier to solve.
   - *Over spray when painting, then remove excess.*
   - *Maximize process for less than 100% yield or conversion*
   - *Reach 100% conversion or yield through the use of excess of reactants*
   - *Flooding a reaction zone with a substance to kill a reaction*

Principle 17. Another dimension

A. To move an object in two- or three-dimensional space.
   - *Infrared computer mouse moves in space, instead of on a surface, for presentations.*
   - *Five-axis cutting tool can be positioned where needed.*

B. Use a multi-story arrangement of objects instead of a single-story arrangement.
   - *Electronic chips on both sides of a printed circuit board*
   - *Multi-story chemical operations to take advantage of gravity flow*
   - *Design of chemical systems which expand in volume under a specified condition*

C. Tilt or re-orient the object, lay it on its side.
   - *Orientation of process equipment to allow access, more desirable mixing or rotation*

D. Use 'another side' of a given area.
   - *Stack microelectronic hybrid circuits to improve density*
   - *Use the internal pores of a solid as a reaction surface*
   - *Use both inner and outer surfaces of heat exchangers, jackets, etc. for useful functions*

Principle 18. Mechanical vibration

A. Cause an object to oscillate or vibrate.
   - *Ultrasonic flow measuring systems*
   - *Systems to improve flow from hoppers*

B. Increase its frequency (even up to the ultrasonic).
   - *Distribute powder with vibration.*

C. Use an object's resonant frequency.

- *Use microwaves for moisture removal*

D. Use piezoelectric vibrators instead of mechanical ones.
   - *Quartz crystal oscillations drive high accuracy clocks.*

E. Use combined ultrasonic and electromagnetic field oscillations.
   - *Mixing alloys in an induction furnace*

Principle 19. Periodic action

A. Instead of continuous action, use periodic or pulsating actions.
   - *Batch vs. continuous reaction processes*
   - *Reciprocal pumps and compressors vs. centrifugal devices*

B. If an action is already periodic, change the periodic magnitude or frequency.
   - *Alternate the cycle of reciprocal devices*
   - *Replace a continuous siren with sound that changes amplitude and frequency*
   - *Use of pulsation to produce extremely small particles in an emulsion system*

C. Use pauses between impulses to perform a different action.
   - *Use variability in pumping systems to introduce new reactants*
   - *Use downtime to do preventative maintenance*

Principle 20. Continuity of useful action

A. Carry on work continuously; make all parts of an object work at full load, all the time.
   - *Flywheel (or hydraulic system) stores energy when a vehicle stops, so the motor can keep running at optimum power*
   - *Run the bottleneck operations in a factory continuously, to reach the optimum pace*

B. Eliminate all idle or intermittent actions or work.
   - *Print during the return of a printer carriage--dot matrix printer, daisy wheel printers, ink jet printers*
   - *Cross train operators to do both plant operations and maintenance*
   - *Use all spare equipment time to produce alternative products*

Principle 21. Skipping

A. Conduct a process, or certain stages (e.g. destructible, harmful or hazardous operations) at high speed.
   - *Control reaction sequence to bypass a hazardous regime*
   - *Minimize reaction times under hazardous conditions*
   - *Cut plastic faster than heat can propagate in the material, to avoid deforming the shape.*

Principle 22. "Blessing in disguise" or "Turn Lemons into Lemonade"

A. Use harmful factors (particularly, harmful effects of the environment or surroundings) to achieve a positive effect.
    - *Use waste heat from one unit operation in another unit operation*
    - *Recycle waste (scrap) material from one process as raw materials for another*
    - *Recover and re-use shipping and packing materials*
B. Eliminate the primary harmful action by adding it to another harmful action to resolve the problem.
    - *Add a buffering material to a corrosive solution.*
    - *Use a helium-oxygen mix for diving, to eliminate both nitrogen narcosis and oxygen poisoning from air and other nitrogen compounds*
    - *Use a backfire to eliminate the fuel from a forest fire*
    - *Use a generated waste as a raw material for another viable process*

Principle 23. Feedback

A. Introduce feedback (referring back, cross-checking) to improve a process or action.
    - *Proportional, integral, and derivative control*
    - *Temperature, pressure, and compositional input to control systems*
    - *Statistical Process Control (SPC) -- Measurements are used to decide when to modify a process*
    - *Budgets –Intermediate measurements are used to decide when to modify a process.*
B. If feedback is already used, change its magnitude or influence.
    - *Change proportionality constants and gains in controller settings*
    - *Add derivative control to add addition sensitivity*
    - *Change a management measure from budget variance to customer satisfaction*

Principle 24. 'Intermediary'

A. Use an intermediary carrier article or intermediary process.
    - *Azeotropic distillation*
    - *Extraction*
    - *Settling and decantation*
    - *Heat transfer solutions*
B. Merge one object temporarily with another (which can be easily removed).
    - *Use extraction to remove a desirable component prior to separation*
    - *Azeotropic distillation*

Principle 25. Self-service

A. Make an object serve itself by performing auxiliary helpful functions

- *A soda fountain pump that runs on the pressure of the carbon dioxide that is used to "fizz" the drinks. This assures that drinks will not be flat, and eliminates the need for sensors.*
- *Halogen lamps regenerate the filament during use--evaporated material is redeposited.*
- *An autocatalytic reaction system*
- *A filtration system whose washing system responds to how dilute eluent becomes*

B. Use waste resources, energy, or substances.
- *Use heat from a process to generate electricity: "Co-generation".*
- *Use mutually available waste heat and cooling in different processes*
- *Use waste packaging as fuel source or for community recycling*

Principle 26. Copying

A. Instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies
- *Use moldings to shape plastic parts*
- *Replace human announcements with automatic recording based on the condition at hand.*

B. Replace an object, or process with optical copies
- *Use 3-D models for training and design*
- *Measure an object by measuring the photograph*
- *Make sonograms to evaluate the status of equipment vs. physically taking apart.*

C. If visible optical copies are already used, move to infrared or ultraviolet copies
- *Make images in infrared to measure heat profiles and assess status of insulation systems.*
- *Use infrared sensing for security monitoring along plant perimeters*
- *Identify process and product elements sensitive to ultraviolet screenings and analysis*

Principle 27. Cheap short-living objects

A. Replace an inexpensive object with a multiple of inexpensive objects, comprising certain qualities (such as service life, for instance)
- *Use disposable paper objects to avoid the cost of cleaning and storing durable objects.*
- *Replace pigment holding objects on assembly robots to avoid cleaning entire painting systems*
- *Use of catalysts in minor quantities that can be filtered out or left in the final product*
- *Constantly removed and replaced filter coating in centrifugal filters*
- *Use building models to train operators and obtain input*

Principle 28 Mechanics substitution

A. Replace a mechanical means with a sensory (optical, acoustic, taste or smell) means
    - *Replace a physical fence to monitor intrusion into hazardous areas with optical and acoustic mechanisms*
    - *Use a mercaptan compound in natural gas to alert users to leakage, instead of a mechanical or electrical sensor*
B. Use electric, magnetic and electromagnetic fields to interact with the object
    - *To mix 2 powders, electro statically charge one positive and the other negative. Either use fields to direct them, or mix them mechanically and let their acquired fields cause the grains of powder to pair up*
    - *Replace pneumatic controls and measurements with electronic and electromagnetic systems*
C. Change from static to movable fields, from unstructured fields to those having structure
    - *Specifically stereo specifically designed catalysts that determine control MW and MWD in polymer systems*
    - *Stereo specific catalysts to control optical rotation of biologically active compounds*
D. Use fields in conjunction with field-activated (e.g. ferromagnetic) particles
    - *Heat a substance containing ferromagnetic material by using varying magnetic field. When the temperature exceeds the Curie point, the material becomes paramagnetic, and no longer absorbs heat*

Principle 29. Pneumatics and hydraulics

A. Use gas and liquid parts of an object instead of solid parts (e.g. inflatable, filled with liquids, air cushion, hydrostatic, hydro-reactive).
    - *Load cells to measure status of raw material storage and reaction vessels*
    - *Store energy from decelerating a vehicle in a hydraulic system, then use the stored energy to accelerate later.*
    - *Pneumatic based process control systems*
    - *Pneumatic conveying, dense and dilute*

Principle 30. Flexible shells and thin films

A. Use flexible shells and thin films instead of three dimensional structures
    - *Plate and frame exchangers*
    - *Gas separation membranes*
B. Isolate the object from the external environment using flexible shells and thin films.
    - *Float a film of bipolar material (one end hydrophilic, one end hydrophobic) on a reservoir to limit evaporation*
    - *Food packaging design to minimize oxygen and moisture transmission*

Principle 31. Porous materials

A. Make an object porous or add porous elements (inserts, coatings, etc.)
    - *Drill holes in a structure to reduce the weight*
    - *Automobile and other porous catalytic systems*
B. If an object is already porous, use the pores to introduce a useful substance or function.
    - *Use a porous metal mesh to wick excess solder away from a joint.*
    - *Store hydrogen in the pores of a palladium sponge. (Fuel "tank" for the hydrogen car--much safer than storing hydrogen gas)*
    - *Use porosity design and variability to control types of chemical reactions*

Principle 32. Color changes

A. Change the color of an object or its external environment.
    - *Use safe lights in a photographic darkroom*
    - *Use of color change to indicate pH change, a sign of reaction completion, or as a sign of problems within a reaction system*
    - *Use of color sensitive labeling on temperature sensitive foods*
B. Change the transparency of an object or its external environment.
    - *Use photolithography to change transparent material to a solid mask for semiconductor processing. Similarly, change mask material from transparent to opaque for silk screen processing*
    - *Transparency change due to phase change as a function of temperature that can be used for window materials, indicate purity of chemical product in manufacturing or use*

Principle 33. Homogeneity

A. Make objects interacting with a given object of the same material (or material with identical properties).
    - *Make the container out of the same material as the contents, to reduce chemical reactions.*
    - *Make a diamond cutting tool out of diamonds*
    - *Use mutual solubility to enhance homogeneous catalysis*
    - *Use third components to achieve azeotropic distillation*

Principle 34. Discarding and recovering

A. Make portions of an object that have fulfilled their functions go away (discard by dissolving, evaporating, etc.) or modify these directly during operation.
    - *Use a dissolving capsule for medicine*
    - *Addition of water to cornstarch-based packaging to reduce its volume by more than 1000X*
    - *Use water ice or carbon dioxide (dry ice) to make a template for a rammed earth structure, such as a temporary dam. Fill with earth, then, let the ice melt or sublime to leave the final structure.*
B. Conversely, restore consumable parts of an object directly in operation.

- *Pre-packaged raw material additives to minimize exposure and minimize errors*
- *Automobile engines that give themselves a "tune up" while running*
- *Auto-catalytic reactions*

Principle 35. Parameter changes

A. A. Change an object's physical state (e.g. to a gas, liquid, or solid)
   - *Freeze the liquid centers of filled candies, then dip in melted chocolate, instead of handling the messy, gooey, hot liquid.*
   - *Transport oxygen or nitrogen or petroleum gas as a liquid, instead of a gas, to reduce volume.*

B. Change the concentration or consistency.
   - *Liquid hand soap is concentrated and more viscous than bar soap at the point of use, making it easier to dispense in the correct amount and more sanitary when shared by several people*
   - *Production of concentrates for dilution by customers on an as required basis*

C. Change the degree of flexibility.
   - *Use adjustable dampers to reduce the noise of parts falling into a container by restricting the motion of the walls of the container*
   - *Vulcanize rubber to change its flexibility and durability*
   - *Addition of plasticizers to rigid polymers to improve their flexibility and cold temperature performance*

D. Change the temperature.
   - *Raise the temperature above the Curie point to change a ferromagnetic substance to a paramagnetic substance.*
   - *Raise the temperature of food to cook it. (Changes taste, aroma, texture, chemical properties, etc.)*
   - *Lower the temperature of medical specimens to preserve them for later analysis*
   - *Control reactors through knowledge of reaction kinetics, decomposition rates, and volatility vs. time*

Principle 36. Phase transitions

A. Use phenomena occurring during phase transitions (e.g. volume changes, loss or absorption of heat, etc.).
   - *Use of phase changes in materials to absorb heat or control its rate of release*
   - *Heat pumps use the heat of vaporization and heat of condensation of a closed thermodynamic cycle to do useful work*
   - *Use expansion and contraction properties of freezing*

Principle 37. Thermal expansion

A. Use thermal expansion (or contraction) of materials.
    - *Fit a tight joint together by cooling the inner part to contract, heating the outer part to expand, putting the joint together, and returning to equilibrium (i.e. plastic lined pipe manufacture)*
    - *Use special joints to minimize physical damage and short circuiting in metal heat exchanges*
B. If thermal expansion is being used, use multiple materials with different coefficients of thermal expansion.
    - *The basic leaf spring thermostat: (2 metals with different coefficients of expansion are linked so that it bends one way when warmer than nominal and the opposite way when cooler.)*
    - *Bi-metallic instrumentation construction*

Principle 38. Strong oxidants

A. Replace common air with oxygen-enriched air
    - *Accelerate oxidation reactions with enriched air*
    - *Membrane air separation technology*
B. Replace enriched air with pure oxygen
    - *Cut at a higher temperature using an oxy-acetylene torch.*
    - *Treat wounds in a high pressure oxygen environment to kill anaerobic bacteria and aid healing*
    - *Further accelerate oxidation reactions*
C. Use ionized oxygen.
    - *Ionize air to trap pollutants in an air filtration equipment*
D. Replace ozonized (or ionized) oxygen with ozone.
    - *Speed up chemical reactions by ionizing the gas before use*
    - *Disinfect highly polluted waste streams*

Principle 39. Inert atmosphere

A. Replace a normal environment with an inert one
    - *Use of nitrogen padding to minimize flammability hazards and to prevent oxidation, fire, or explosion*
    - *Use of argon when nitrogen may react with certain products at high temperature*
B. Add neutral parts, or inert additives to an object
    - *Add inert fillers to products (detergents, pharmaceuticals) to increase bulk or to improve functionality.*
    - *Add inert plugs to pipeline transfers to minimize mixing of transported fluids*

Principle 40. Composite materials

A. Change from uniform to composite (multiple) materials

- *Use of composites for superior product performance in golf clubs, airplane parts, chemical tanks*
- *Use of multi-layer polymers for barrier protection, membranes, and other unique polymer properties*