A PROTOTYPE SYSTEM OF BUILDING FOR EDUCATION

by

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B. Arch., University of Minnesota, 1961

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Dear Dean Anderson:

In partial fulfillment of the requirements for the degree of Master of Architecture, I hereby submit this thesis, entitled "A Prototype System of Building for Education."

Respectfully,

David Leroy Pavelka
ABSTRACT

Title of Thesis: A PROTOTYPE SYSTEM OF BUILDING FOR EDUCATION

Author: David Leroy Pavelka

Submitted to the Department of Architecture on August 15, 1966 in partial fulfillment of the requirements for the degree of Master of Architecture.

The objective of this thesis is to develop a structural system which allows for growth and flexibility. This structural system must integrate the requirements for mechanical services. The building is to be conceived as a total system of circulation, services, and construction.

The latest technology of precast concrete is to be used with total standardization of form work. Ease of transporting components to the site, speed of erection and quality control obtained by mass production of components at the factory are to be considered.

Therefore, the objective is a building as a system of growth, structure, and services.

Thesis Supervisor: Eduardo F. Catalano

Title: Professor of Architecture
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Professor Waclaw Zalewski, Structures
Mr. Sidney Greenleaf, Mechanical Systems
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I. INTRODUCTION

Systems oriented architecture is in a very primitive state today. To build at large scale in a systematic manner which allows for growth and flexibility is a problem which architects have neglected. In a sense, architects have become merely stylists. Today's needs require a new vocabulary based on our technological advancements. A system of building must be developed which allows for orderly growth, interior and exterior spatial flexibility, and logical vertical and horizontal circulation patterns for occupants and mechanical services. A basic geometric unit must be established which is self sufficient structurally and mechanically. This basic unit may be combined with other similar units to meet varying building programs. Permanent elements and temporary elements within the building must be sorted out. Certain vital elements become permanent components such as cores, columns, girders, and main mechanical branches. Secondary components such as beams and secondary mechanical service branches can change or be removed to achieve flexibility in use or variety through spatial changes. These components are then considered temporary. This hierarchy of building elements permits continued use of the building long after its original intended use no longer exists. Buildings today become obsolete much before the life span of their physical shell.
II. DESIGN APPROACH

To be built in a systematic manner, architecture for educational facilities requires a dimensioned framework which is expressed graphically in plan and section. Footprints of a structure are made by its columns, cores and spanning elements. The basic design approach is to develop a wallpaper plan which shows these components. Plan variations (stimulated by varying programmatic requirements) are superimposed over this wallpaper adhering to the grammatical rules of the building system.

The planning problem to be solved is that of bay size, module selection, core design and column design. Flexibility and growth patterns of lineal or one-way structural systems versus two-way structural systems are studied and evaluated.

Integration of the permanent mechanical services within the structure and access to the temporary mechanical services is of primary importance. Maximum uninterrupted floor area, minimum depth of floor structure, maximum spatial variation, and simplicity in mechanical distribution and return patterns are also important design considerations.

III. GENERAL DESCRIPTION

A lineal, precast, prestressed reinforced concrete structural system of columns, girders and beam channels
was developed with a poured in place leveling and topping slab. The clearspan bay size is twenty-five feet by fifty feet. The planning module is five feet by ten feet. The construction depth is two feet six inches including a three inch topping slab.

Modular cores containing the basic elements of fire stairs, passenger elevators, vertical mechanical shafts, freight elevators, and lavatories were developed within the fifty foot span between girders. Axial dimensions in increments of the five foot module.

The mechanical system for air conditioning utilizes the space between the double girders for horizontal distribution to the channel beams. Cores provide the supply and return of air for the interior zone of the building. Columns provide the supply for the fifteen foot perimeter zone of the basic unit.

The basic unit of five bays in the axial direction and three bays in the longitudinal direction is the maximum floor area for the fire stair requirements as dictated by the National Fire Code. Axial and/or longitudinal expansion is accomplished utilizing multiples of the basic unit.

A. System Selection

The primary system classifications are:

1. One-way or lineal
2. Two-way

The most direct and commonly used framing system is
the one-way system. Beams and major girders transfer loads to the columns. Only in the most sophisticated applications of the one-way system are both prestressing and post-tensioning performed. The prestressing carries the stresses due to dead loads; the post-tensioning carries live loads and the topping slab acts as a diaphragm for structural continuity. Flexibility in mechanical service distribution is limited. The structure is directional and the distribution of the stresses in a bay is evident in the differentiation of the sizes of the members.

The two-way system requires post-tensioning in two directions forming a two-way matrix. Currently this is a complex and costly operation. Post-tensioning involves the use of jacks and threading cables through a structure. Major difficulties arise in joints between members which must be over dimensioned to accommodate compressive forces due to post-tensioning. Deviations in positioning holes for post-tensioning cables requires over dimensioning the holes. Two-way systems usually make extensive use of scaffolding.

Since both one way and two way systems offer degrees of spatial flexibility and growth and since feasibility is based on economic studies, a qualitative decision was made. In this thesis a one-way system was selected over a two-way structural system since preliminary studies showed interior spatial flexibility could be achieved with greater
structural ease. Generally, less post-tensioning, less scaffolding and a lesser number of components are necessary to construct a given bay size.

B. Module Selection

The determinates of a good module are the result of weighing the following factors:

1. Space planning
2. Structural systems
   e. Mechanical systems

A five foot by ten foot module was selected. This module produces a smallest habitable space of nine feet six inches by nine feet six inches (two modules minus partition dimensions) and the next largest space of nine feet six inches by fourteen feet six inches (three modules). These spaces were considered satisfactory for offices in a building for education. Satisfactory intradepartmental circulation can be accomplished in a four foot six inch space (one module). Primary circulation can be accommodated within dimensions of nine feet six inches or fourteen feet six inches.

The dimensions of beams in a beam and girder precast system are a significant factor in module selection. Since the transporting of members is critical to a successful precast system, it was felt that structural members should not exceed sixty feet. It is also desirable that beam members should not be less than forty feet in length. The
establishment of a lineal system influenced the decision in favor of a rectangular module.

Spacing of luminaires and air conditioning diffusers, while somewhat more flexible than the space planning and structural systems factors, are module determinants. The use of standard length luminaires and a regular pattern of diffusers does reduce the cost of a mechanical system. A five foot by ten foot module easily accommodates two standard eight foot, forty watt fluorescent lamps in each module. This produces an even distribution of light at 100 foot-candles at the three foot working surface. Two-inch wide strip diffusers located ten feet on center provide an even distribution of air for large spaces as well as small.

Since the column is important to the vertical supply of the mechanical system as well as the structural system, the dimensions of the column should not only coincide with the structural module but should also provide adequate space for ducts and pipes. A five foot by five foot space provides adequately for these two functions.

While other modules may more ideally meet the requirements of one or more of the above factors, the five foot by ten foot module most adequately meets all of the factors.

C. Bay Size Selection

Three primary factors dictated the final bay size after the five foot by ten foot module had been selected:

1. The desire to provide large spaces uninterrupted by columns for planning flexibility.
2. The desire to have the girders flush with the beam channels and therefore eliminate a special condition when interior partitions meet the girder.

3. The desire to keep the structural depth of the floor minimal.

Program requirements for education buildings, only in exceptional cases, require spaces wider than fifty feet. Exceptions to this planning factor are large auditoriums. It was felt that these could be handled as special conditions within an education complex since the requirement is unusual.

A two to one ratio of length of beam channel to girder within a given bay gives a flush ceiling. Therefore, with one dimension fixed at fifty feet the clearspan for the girder becomes twenty five feet. While this limits uninterrupted floor space in the longitudinal direction, spaces can be obtained which are fifty feet wide and which have a length dictated only by the physical dimension of the entire building.

The length of span in a reinforced concrete structure divided by twenty gives the depth of structure. Therefore:

\[
\text{Beam channel: } \frac{50 \text{ ft}}{20} = 2.5 \text{ ft.}
\]

The structural depth of two feet six inches was found to be adequate for the passage of low velocity air conditioning ducts (maximum duct dimension with insulation being
eight inches by twelve inches to service an area ten feet by fifty feet), the luminaires (four inches), and the acoustic panels (one inch).

D. The Core

Centrally located in the basic unit is the core containing all those elements which perforate a structure vertically. Primary vertical air conditioning shafts, electrical and telephone terminal boxes for each floor, passenger and freight elevator shafts, fire stairs, and rest rooms are included in this service core. The central position of the core insures equal distribution of services to all parts of the building. Developed on a module of five feet (as illustrated on the plan variation drawing) the core has four variations based on varying programmatic requirements.

1. The fire stair with five feet by fifteen feet vertical mechanical shafts on each end would be used if the structure were less than three stories high. The overall dimension is fifty feet by fifteen feet.

2. Passenger elevators, fire stairs and vertical mechanical shafts would be used if the building were four or more stories high. This core variation has an overall dimension of twenty five feet by fifty feet.

3. Freight elevator, men and women's rest rooms, passenger elevators, fire stairs and mechanical shaft are considered the typical minimum complete unit for an average five story building. The overall dimensions of this core
variation is thirty feet by fifty feet.

4. A freight lobby, a janitor's closet, and larger rest rooms in addition to the items mentioned above are included in the fourth modular variation. This fifty five by fifty foot core can be utilized where extremely heavy usage occurs.

Cores in all cases fill the entire span of fifty feet. The precast girders tie into the poured in place core walls. This tie enables the core walls to take longitudinal and axial shear. For the entire structure, general planning factors which determined the size of the cores are:

1. "Group 'D' buildings ... distance of travel to nearest exit shall not exceed 150 feet from any point." (National Fire Protection Code, paragraph 2243).

2. "Fire stair width shall be a minimum of six units (one unit equals 22 inches)." This may be two scissor stairs of 3 units each as shown on the typical plan drawing. (National Fire Protection Code, paragraphs 2202, 2103, 3011-3013, and 2272).

3. One six foot by eight foot elevator in a five story building serves a net area of 85,000 square feet.

Therefore: \[
\frac{\text{Total area of basic unit}}{\text{Area served by one elevator}} = \text{number of elevators}
\]

\[
\frac{162,500}{85,000} = 2
\]

4. One electrical closet has twenty square feet for every 15,000 square feet of gross area.
5. One telephone closet has fifty square feet for every 15,000 square feet.

6. One janitor's closet has thirty square feet for every 30,000 square feet of gross area.

7. One service elevator is adequate to service two basic units (162,500 square feet each) in a five story building.

8. Plumbing section (assuming 200 people per floor):

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(Graphic Standards, 5th edition, p. 520, "Schools")

9. Return air shafts (low velocity - 700 fpm) require one square foot per 1,000 square feet of floor area. Supply (high velocity - 4,000 fpm) requires one square foot per 4,000 square feet of floor area. More specific formulae for vertical duct sizes is included in the section on mechanical - interior zone.

IV. STRUCTURAL ELEMENTS

A. The Beam Channel

The geometry of the beam channel is dictated by the configuration of the girder, the necessity of providing a working floor surface during construction, the space requirements for return air voids between the channels, the space requirements for the temporary air supply ducts which must
be accessible from below, and the requirements for acoustical sound absorption panels, lighting and pipes. In addition to these basic and very functional requirements, there is an unwritten but equally important requirement for a visually pleasing ceiling. Also necessary is a continuous ceiling grid for partition abutment. In this design the diaphragms are not simply false partition abutments. They are required structurally to prevent the inclined walls of the beam channel from spreading. The diaphragms are therefore ties which bind the beam channel walls together.

The length of the beam channel is fifty feet. Its width is four feet ten inches allowing a two inch void between beam channels at the ceiling plane. This void splays to a two feet six inch dimension at the floor plane where it is sealed by a precast concrete filler piece. The void is the return air duct for the air conditioning system. Since return air ducts require no insulation, the concrete of the channel beams actually form the duct.

Because the configuration of the beam channel was not determined primarily by a method of forming, several methods of casting are feasible. The first and most technologically compatible method is a single monolithic cast. Form work for the channel beam consists of three elements: the coffer mold, and two symmetrical side forms. Knock out form work is placed above the diaphragms to allow the passage of supply ducts and pipes.
Another method consists of precasting the diaphragms, precasting and pretensioning the fifty foot tension cords, positioning these elements around five coffer forms, welding the steel projecting from the precast pieces to a wire mesh and utilizing a sprayed concrete (Gunite Method) to complete the walls and top of the channel beam. This technique may be more complex; however, the quality of concrete for each element could be controlled and those elements which work the hardest in the structure would be made of better quality concrete. If done in a large quantity, this method could prove to be the most economical. Form work in this case could be made of either steel or molded plastic.

Consideration was given to the transporting of the channel girders after casting at a central plant. The length of fifty feet was considered a feasible length for loading and transporting. The calculated weight of one beam channel is twelve kips. Five beam channels could be transported by one truck simultaneously and still be within thirty ton road weight limits.

The cantilever of the beam channel may be either ten feet or fifteen feet. This cantilever must always be backed by a standard fifty foot beam channel. Scaffolding is required to position the cantilevered, precast beam channel before it is tied to the backing beam channel. This tie is accomplished by post tensioning. A Ryerson unbonded tendon post tensioning technique is utilized. The tendon is thirty
feet long in the case of the fifteen foot cantilever and twenty-five feet long in the case of the ten foot cantilever. The post tensioning process is accomplished from above utilizing the working surface of the channel beams and the filler piece over the girder. The cable is passed through a pipe which is cast in the beam channel. Adequate space is available for the hydraulic jack required, the dimensions of which are six and one half inches in diameter and forty-six inches in length.

B. The Girder

Two girder lengths are provided within the system. To facilitate a cantilever at the exterior edge of the structure and to facilitate multi-story voids within the structure, the primary girder was given a length of fifty-five feet. Secondary girders bridge the gap between the cantilevers of the primary girders.

The clearspan between columns of twenty-five feet dictated the structural depth of two feet six inches. A beam cross section one foot wide and one foot six inches deep is sufficient to carry the dead load of the structure. Reinforcing steel is tied to the steel of the topping slab to increase the effective girder depth to two feet six inches. This increase in effective girder depth allows the girder to carry the total dead and live loads. The total load is two hundred pounds per square foot.

Concrete trapezoidal transition projections encase
the girder-to-slab steel ties. This vertical girder projection acts also as a guide for the placing of the beam channel. Voids between the vertical concrete projections on the girder allow duct work, pipes, wiring and communications equipment to pass over the girder and under filler pieces and leveling slab.

The girders would be cast on their sides. Since the girders are flush with the bottom of the beam channels only the bottom of the girder is visible. The weight of the fifty five foot long girder is 14.8 kips and the weight of the fifteen foot long girder is 4.6 kips. Truck transporting of these elements is feasible.

C. The Column

The column is so designed that one, two and three story heights can be cast at the factory and transported to the site. The reinforcing is varied to meet these particular height requirements. This vertical spatial flexibility does not create a special condition within the structure since girders and channel beams are merely omitted. The column is tied to the girder by post-tensioning. Grooves are cast in the column so that the one inch steel cable is visible and accessible during construction. The grooves are grouted after the columns and girders are bound together to meet fireproofing codes. A reveal one half inch deep and two and one half inches wide running the entire length of the column is the final visual product. Steel angles forming
a box are cast into the top of the column. Grout and leveling shims are placed in this box prior to the positioning of the girder. A one inch set back is visible at the top of the column. The column dimensions are one foot by five feet in plan.

Whether the columns are precast or cast "in situ" is not critical to the design solution. However, it is felt that there is some advantage to a totally precast system which is shipped to the site and wet concrete used on the site for grouting and leveling slabs.

D. Filler Pieces

Within this structural system there are three precast filler pieces required.

1. Beam channel fillers
2. Girder fillers
3. Transverse compression bars between girders

The beam channel filler pieces are designed as small light-weight panels which bridge the two foot six inch gap between the top surfaces of the beam channel. The dimensions of the piece are one foot by two feet six inches by one inch. Weighing only thirty pounds, each piece is easily put in place by a workman on the site. These filler pieces serve only as a base for the topping slab and are not structural.

Girder fillers are similar, not structural and serve as a base for the leveling and topping slab. Two sizes are
required: panels five feet by ten feet by two inches and panels five feet by five feet by two inches. Grooves in these pieces assist workmen on the site positioning steel in the topping slab. The weight of these pieces is .63 kips and .315 kips respectively.

Structural transverse compression members are required between the girders where there is a cantilever in the beam channel. Eight inches by eight inches by three feet are the dimensions of these pieces which are bolted in place after the girders are placed.

E. THE CONSTRUCTION SEQUENCE

1. Footings and basement floor are poured.
2. Core walls are poured to first floor. Columns are positioned and secured to footings.
3. Girders are placed on the grouted columns and bonded.
4. Beam channels are positioned on the girders.
5. Filler pieces are placed on the beam channels and girders.
6. Transverse compression pieces are bolted in place.
7. Electrical bus ducts are layed on precast floor surface. Leveling slab steel is placed and the leveling slab is poured.
8. Columns are positioned for the next floor and steps 2 through 7 are repeated.
9. Exterior walls are set in. Mechanical duct work, electrical wiring, lighting, acoustic treatment, piping,
and interior partitions are installed, thereby finishing the space.

V. MECHANICAL SYSTEM

A. General Theory

The technology of mechanical systems is changing rapidly. For complete climate control, windows are fixed and the building is sealed. Air conditioning provides heating, cooling, ventilation, and humidity control. The trend is toward smaller, less conspicuous, more efficient duct work and diffusers.

A typical floor in a building has two general zones of air conditioning: an interior zone and an exterior zone. Air conditioning in the interior zone is fairly constant while the exterior zone acts as the shock absorber for solar heat gain through the glass. The north side of a building has far less heat gain than the south side. East and west orientations vary with the time of day. Therefore, the exterior zone must have more points of thermostat control. The exterior zone is generally considered to extend fifteen to twenty feet from the exterior wall into the building. Two separate systems are required to properly air condition a building.

Air conditioning systems available today for interior zones are:

1. Low velocity - single duct
   a. With same temperature all over, no individual control
b. With heat coils at diffusers to create individually controlled temperature zones

2. High velocity - single duct
   a. With low velocity transition box and sound attenuation at diffuser, same temperature all over
   b. With transition box and sound attenuation to change high velocity to low velocity at point of transition in ducts from primary to secondary and coils at diffusers to provide individual temperature control

3. High velocity - dual duct (one hot, one cold)
   Mixing boxes and sound attenuators required to change to low velocity and provide individual temperature control.

Air conditioning systems in common use today for the exterior zone are:

1. Perimeter induction units
   Utilizes high velocity air with pipes carrying hot and cold supply and return water

2. Dual duct high velocity
   With mixing boxes at sill or ceiling
3. Fan coil units
   a. Utilizing pipes containing hot and cold water at sill level, plus holes in the exterior face for fresh air intake
   b. Utilizing pipes containing hot and cold water at sill level plus recirculation of air from the perimeter zone

Calculations for duct sizes are based on high velocity air at 4000 fpm to 5000 fpm and low velocity at 1200 fpm. Low velocity return air is considered at 700 fpm. Return air is generally 75% of the supply. Toilette exhaust is calculated at twelve air changes per hour at 1000 fpm.

Rules of thumb for calculating duct sizes:

1. High velocity (4000 fpm)
   a. Cold air - .38 sq ft duct area/10,000 cu ft
   b. Hot air - .28 sq ft duct area/10,000 cu ft

2. Low velocity (1200 fpm)
   1.25 sq ft duct area/10,000 cu ft

3. Return air (700 fpm)
   1.5 sq ft duct area/10,000 cu ft

In this thesis the primary mechanical equipment is located on the roof above the cores. Fresh air intake grills and heating and cooling equipment are also located in this penthouse. A mechanical bridge links the columns feeding the perimeter system to the core penthouse. Since the
cross-sectional area of the columns diminishes at the upper levels more space is available for larger ducts which feed down. A high velocity-dual duct system is used through the building for primary distribution.

Electrical and telephone service originate from electrical closets in the service cores at each floor. Distribution conduits are layed in a five foot grid on the precast floor system prior to the pouring of the three inch topping slab. Terminals flush with the finished floor may be tapped as required; thus every space has flexibility in location of recepticals, telephones and intra-building communication systems.

B. Air Conditioning - Interior Zone

Cores provide the vertical duct space for the interior zone. The eight foot wide space between the girders flanking either side of the core contains the primary horizontal ducts. A dual duct system is used to this point. Velocity reducing, sound attenuating mixing boxes are located ten feet on center at the ends of alternating channel beams. Low velocity air is fed through alternating channel beams with strip diffusers ten feet on center throughout the space. When the space is two stories high supply ducts are placed in each channel beam with strip diffusers five feet on center throughout the space.
C. Air Conditioning - Exterior Zone

Columns provide the vertical high velocity dual duct space for the axial exterior zones. Cores provide the vertical high velocity dual duct space for the transverse exterior zones. Extensions are made to the dual ducts located between the girders adjacent to the cores. Sound attenuating, velocity reducing mixing boxes are located ten feet on center in both axial and transverse perimeter zones.

Conversion from exterior to interior zone in the event of building expansion is easily accomplished. Since the primary vertical and horizontal ducts are fixed, and the sound attenuating, velocity reducing mixing boxes are located ten feet on center at the ends of the new channel beams, all that remains to be done is connect the new low velocity ducts located in the new channel beams to the mixing boxes.

D. Lighting

With a standard ceiling height of twelve feet for classrooms, two eight foot fluorescent tubes located in each five foot by ten foot module provide 100 foot candles of light at the working surface which is three feet above the floor.

When a two story space occurs additional fluorescent tubes would be added. Space within the coffer allows for up to four fluorescent tubes per coffer. High output tubes could be utilized to increase lighting levels.
Since the tubes are recessed within the coffer one foot three inches, only those tubes which are directly over head and those two coffers ahead of the viewer are visible. Beyond this point only the lighted plane of the concrete coffer is visible.

E. Acoustics

When the structure is expressed in a reinforced concrete building, acoustical treatment must be included in the design concept. In this thesis sound absorptive material is placed in the ceiling coffers above the fluorescent tubes. The acoustic panels are one foot six inches above the bottom edge of the channel beam and have an overall dimension of nine feet six inches by three feet. The effective area is only twenty four square feet due to the fact that the strip diffusers occupy a space of two inches by nine feet six inches. The reverberation time is calculated by Sabines' formula:

\[ R.T. = \frac{0.05V}{a} \]

where

- \( R.T. \) = Reverberation time in seconds
- \( V \) = Volume of the space in cubic feet
- \( a \) = Sum of the surface areas within the space multiplied times their coefficients of absorption or \( (a = \Sigma S \alpha) \)

For the smallest inhabitable space of nine feet six inches square with a twelve foot ceiling

\[ V = 9.5' \times 9.5' \times 12' = 1083 \text{ ft}^3 \]
A reverberation time of .6 secs is desirable for an office space where speech intelligibility is the primary concern. Since reverberation time in large spaces varies directly with the volume of the space and inversely with the amount of sound absorptive material, the range of reverberation for these spaces is .6 secs to 1.4 secs. This range is desirable for speech in the middle frequency range of five hundred cycles per second.

Noise reduction through six inch concrete block partitions is forty decibels which is considered sufficient for educational facilities. Sound transmission is impeded in the transverse direction of the beam channel by the diaphragms. Sound absorbing acoustic baffles are placed in the return air structural voids as required.
PLAN VARIATIONS

A PROTOTYPE SYSTEM OF BUILDING FOR EDUCATION

MASTER IN ARCHITECTURE THESIS  D. L. PAVELKA  M.I.T.  1966
A PROTOTYPE SYSTEM OF BUILDING FOR EDUCATION

SECTION VARIATIONS

LONGITUDINAL SECTIONS
A prototype system of building for education

Master in Architecture Thesis

D.L. Paylera
M.I.T. 1966
GIRDER REINFORCING

CHANNEL REINFORCING

FILLER PANELS & TOPPING SLAB
- perimeter mechanical system
- double duct high velocity
- electrical conduits in deck 5` 11c.

MECHANICAL
- supply diffuser
- return air
- high velocity
- lighting of fluorescent tubes
- acoustic panels
- 24 sq. ft. / 1` 6` 10 module

AXIAL SECTION

A PROTOTYPE SYSTEM OF BUILDING FOR EDUCATION

MASTER IN ARCHITECTURE THESIS
D. L. PAVELKA
MIT 1966
A prototype system of building for education

Master in Architecture Thesis

D. L. Pavelka
N. Y. 1968