# COMPUTER ANALYSIS OF BUILDING-VENTILATION AND HEATING PROBLEMS

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## ABSTRACT

This paper presents a mathematical model, implemented in a general computer code, that can provide detailed information on the velocity and temperature fields prevailing in three-dimensional buildings of any geometrical complexity, for a given ventilation and heating arrangement. The model is based on the partial differential equations governing flow and heat transfer in large enclosures, containing heat sources. Turbulent flow is simulated and account is taken of buoyancy effects on both mean and fluctuating motions.

Two cases are considered, to demonstrate the capabilities of the present model, both referring to actual existing television studios. The program calculates the velocity and temperature fields throughout the three-dimensional configurations, and the results are presented in the form of velocity vectors and temperature contours.

The same procedure is applicable to any problem of heating, cooling, insulation and ventilation of buildings, predicting within practical resources the thermal and fluid-dynamics behaviour of the relevant systems.

## KEYWORDS

Mathematical models; computer simulation; turbulent buoyant convection; building ventilation; three-dimensional configurations.

## INTRODUCTION

The purpose of developing efficient ventilation and heating systems for buldings is to provide comfortable conditions for the people in them, both in terms of air temperature and velocity. Thus, a design that does not maintain a constant temperature of comfortable level is as inefficient as one that does but at the expense of creating unacceptably strong air currents. Furthermore, for audio studios for example, an additional design consideration is the noise level produced by the velocity gradients; high noise levels are transmitted to the microphones and lead to deterioration of the studio's acoustic quality. For the above reasons, it is important that detailed information becomes available on the velocity and temperature fields prevailing in a building of a given design, for a given ventilation and heating arrangement. The objective of this work is to demonstrate how a mathematical model, implemented in a general computer code, can provide this information in three-dimensional buildings of any geometrical complexity. A computational model of this kind, when fully validated, can provide the designer with powerful and economical means of evaluating alternative designs and energy sources.

## MATHEMATICAL FORMULATION

### The Differential Equations

The governing equations, describing the conservation of mass, momentum and energy can be written in the following general form: .

Conservation of mass

$$\frac{\partial \rho}{\partial t} + \text{div}\,(\rho \vec{V}) = 0 \qquad (1)$$

Conservation of fluid property, $\phi$

$$\frac{\partial(\rho\phi)}{\partial t} + \text{div}\,(\rho\vec{V}\phi - \Gamma_\phi \,\text{grad}\,\phi) = S_\phi \qquad (2)$$

where $\phi$ stands for the general conserved property, t for time, $\rho$ for density, $\vec{V}$ for the velocity vector, $\Gamma_\phi$ for the exchange coefficient and $S_\phi$ for the source/sink of $\phi$ per unit volume. $\phi$ for the problems under consideration represents the three velocity components u, v, w in the three space coordinates x, y, z, the stagnation enthalpy $\tilde{h}$ (or temperature T), the kinetic energy of turbulence k, and the eddy dissipation rate, $\varepsilon$. $\Gamma_\phi$ and $S_\phi$ for these variables have been given elsewhere (Markatos and Cox, 1982) and are not repeated here. Buoyancy sources are included in the appropriate momentum equation. The generation terms of the k equation include both the shear production and the buoyancy production (Rodi, 1978; Markatos, Malin and Cox, 1982; Markatos and Cox, 1982). Further details may be found in the above references.

### The Solution Method

The finite-domain technique is used which combines features of the methods of Patankar and Spalding (1972) and Spalding (1980), and a whole-field pressure-correction solver. The space dimensions (and time for transient cases) are discretised into finite intervals; and the variables are computed at only a finite number of locations, at the so-called "grid-points". These variables are connected with each other by algebraic equations (finite-domain equations) derived from their differential counterparts by integration over the control volumes or cells defined by the above intervals. This leads to equations of the form:

$$\sum_n (A_n^\phi + C)\phi_P = \sum_n A_n^\phi \phi_n + CV \qquad (3)$$

where the summation n is over the cells adjacent to a defined point P. The coefficients $A_n^\phi$, which account for convective and diffusive fluxes across the elemental cell, are formulated using upwind differencing. The source terms are written in the linear form $S_\phi = C(V - \phi)$ where C, V stand for a coefficient and a value of the variable $\phi$. The pressure-correction equation is deduced from the finite-domain form of the continuity equation.

The "SIMPLEST" practice of Spalding (1980) is followed, in which the finite-domain coefficients of the momentum equations contain only diffusion contributions, the convection terms being added to the linearised source term. Upwind differencing for convection and harmonic averaging for diffusion are used. The w-momentum equation is solved by TDMA and the u and v by a Jacobi point-by-point procedure. The pressure-correction equation is solved over the whole-field (3D simultaneous solution). More details may be found in above references.

The solution procedure is incorporated into a general computer program for the solution of multi-dimensional, multi-phase problems, which has been described elsewhere (Spalding, 1981; Markatos, Rhodes and Tatchell, 1982; Markatos, 1983).

## Irregular Geometries

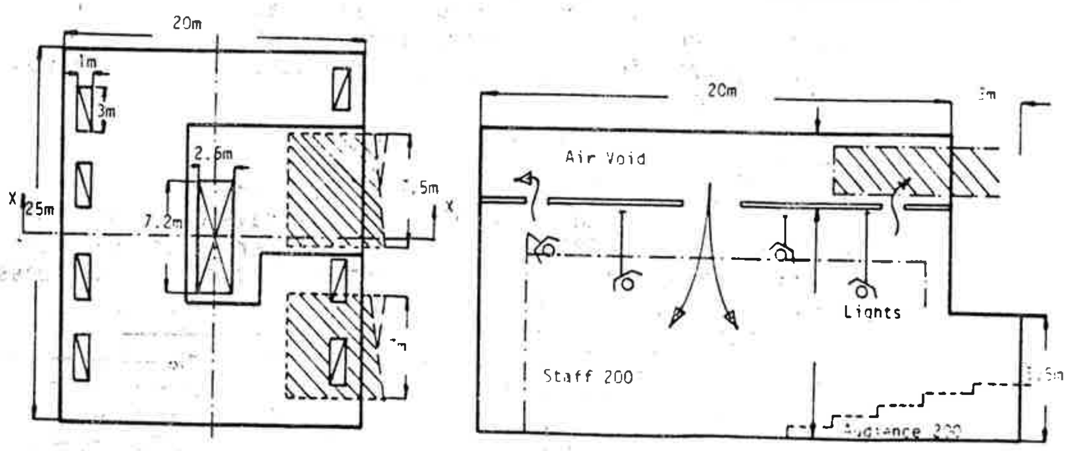
Irregular geometrical features encountered in buildings as well as objects inside them are modelled by use of "porosities" (Spalding, 1981; Markatos and Mukerjee, 1981; Markatos, 1983).

In this approach, each cell in the domain is characterised by a set of fractions, normally in the range from 0 to 1. These fractions determine the proportion of the cell volume which is available for the fluid, and the proportion of each cell-face area available for flow, by convection or diffusion, from the cell to its neighbour in a given direction.

# APPLICATION OF THE MODEL

## Test Cases Considered

The simulation is concerned with the flow and heat transfer of ventilation air in large enclosures, containing heat sources. Two cases are considered both referring to television studios located in London, during performance. The two different configurations are illustrated in Figs. 1 and 2. In both cases ventilation air is




Plan View at Studio Ceiling | Section XX Through Studio

Fig. 1. The Geometry Considered: Studio 1

brought into the studio through the ceiling, after passing through the supply silencers. This air jet penetrates into the studio, gets heated by the heat released by the lights and the actors/spectators, and rises towards the ceiling where it is extracted through the return silencers. The first configuration (Fig. 1), referred to in what follows as studio 1, includes seven extraction vents and a tiered seating area for spectators (Fig. 1); the remaining floor area being used as the stage for actors. The second configuration, Fig. 2, referred to as Studio 2, includes four extraction vents and no specially-designed seating area like Studio 1. Other pertinent input information is given in Table 1. The program calculates the velocity and temperature fields throught the 3D configurations described above. Three studies were performed; two using the input given in Table 1, and the third being for Studio 1, when the lights are switched off. Within each study several configurations for the inlets of the ventilation air were considered.

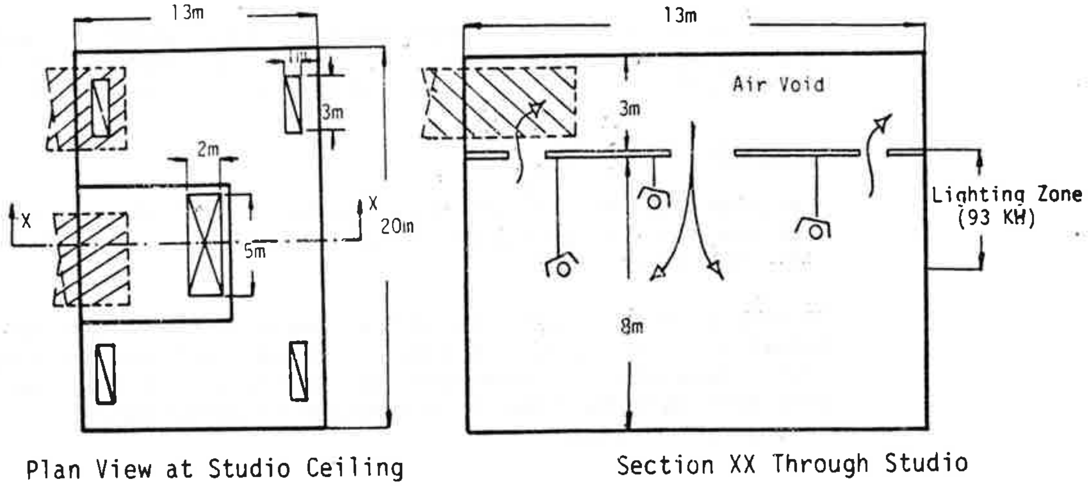



Fig. 2. The Geometry Considered: Studio 2

TABLE 1 Input Data Used in the Computations

| Data | Studio 1 | Studio 2 |
|---|---|---|
| Air Volumes | | |
| Supply ($m^3/s$) | 18.0 | 9.0 |
| Extract ($m^3/s$) | 18.5 | 9.24 |
| Air Temperature ($^oC$ dry bulb) | 12.0 | 12.0 |
| Air Velocity | | |
| Supply (m/s) | 1.0 | 0.9 |
| Extract (m/s) | 0.9 | 0.75 |
| Heat released by lights (total over lighting zone, KW) | 150.0 | 93.0 |
| Heat released by each sitting spectator (KW) | 0.05 | - |
| No. of spectators (max) | 200 | - |
| Heat released by each performing actor (KW) | 0.1 | 0.1 |
| No. of actors (max) | 200 | 100 |

## Boundary Conditions

Boundary conditions are specified as follows. At the ventillation air inlets a fixed mass flow rate is specified and also the values of velocity and temperature that this flow rate is bringing into the domain. At the extraction vents a fixed mass-extraction rate is the specified boundary condition for all vents. At the walls the no-slip condition is applied for the velocities, and wall-functions (Patankar and Spalding, 1972) are used to calculate the wall shear-stress. The walls are assumed adiabatic. Finally, the heat sources released by the performing actors, spectators, and the lights are added.

## Physical Properties

The air viscosity is set to $\mu = 1.8 \times 10^{-5}$ kg/ms. The density is calculated as the following function of temperature, $\rho = 1/2.87 \times 10^{-3}$ T.

## Grid-Dependence and Computer Storage

The reported results have been obtained using a non-uniform grid consisting of 13 cells in the x-direction, 16 in the y- and 13 in the z-direction. The solutions reported are believed to be not fully independent of the grid. The extent of this dependence has not been ascertained.

The program required 257 kilobytes of storage on a Perkin-Elmer 3220 mini-computer, of which 80 kilobytes was for incore storage of variables, with the remainder taken by the program object code.

## Convergence and Computer Time

Good convergence was obtained after 400 sweeps of the domain, as judged by the magnitude of the absolute continuity error which was reduced to 0.3% of the incoming volume flow rate; the monitoring values of variables changing only at the fourth decimal place. Relaxation of the "false transient" type was used for the three velocity components, the value of the "false time step" being 0.1s for all of them. The converged, 400-sweep run with the 13 x 16 x 13 grid required 295 minutes CPU time on the Perkin-Elmer 3220 mini-computer. It should be mentioned that once a converged solution has been generated, it can be used as initial guess for other runs that will then require much less time. Thus the run of Studio 1 with the lights switched off required only 50 sweeps to reach the same level of convergence, when restarted from the solution for Studio 1 with lights on.

## RESULTS AND DISCUSSION

Some of the results of the study are presented in Figures 4 to 14 in the form of velocity vectors and of isotherms. They have been obtained using GRAFFIC (Markatos and Pericleous, 1983). Figures 3 to 5 refer to the case of Studio 1 with the lights on. Figure 3 presents velocity vectors on the z-y plane passing through the middle of the studio.

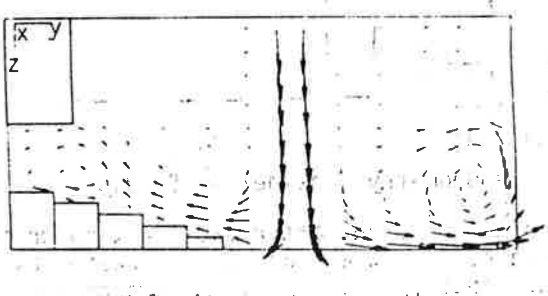



Fig. 3 Velocity vectors on the z-y plane passing through the middle of Studio 1 (max. velocity = 1.45 m/s)

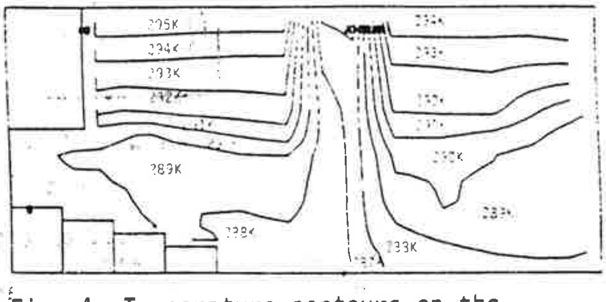


Fig. 4 Temperature contours on the middle z-y plane (Range 285 K to 295 K in 10 equal intervals)

It is seen that the cool air jet penetrates deeply in the Studio, reaches the floor and is then deflected outwards, towards the locations of the spectators and actors. Two vortices are observed: one on the stage where the actors are performing, and a weaker one at the top of the seating area for the spectators. Very low velocities prevail near the ceiling, away from the jet. Inspection of the field c the w-velocity component (the vertical component) reveals that along horizontal cross-sections w is of appreciable magnitude (up to 1.45 m/s) directly beneath the inlets and diminishes further away. The max w at the cross-section located 5.5 m below the ceiling is 1.38 m/s and diminishes to 0.6 m/s at the cross-section locat 0.75 m above the floor. These velocities are considered high from the design poin of view.

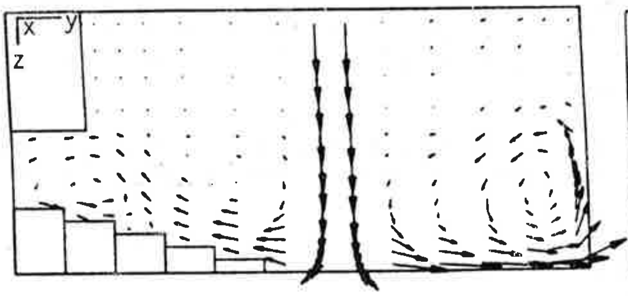



Fig. 5 Velocity vectors on the z-y plane passing through the middle of the Studio. Lights switched off (max. velocity = 1.20 m/s)

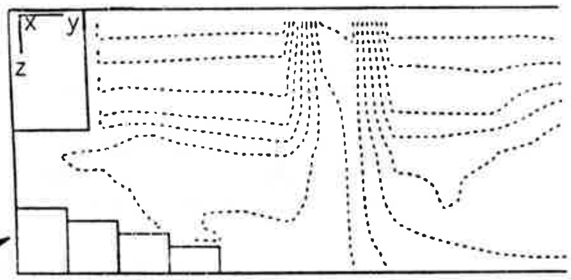



Fig. 6 Temperature contours on the middle z-y plane. Lights off (temperature range 285 K to 288 in ten equal intervals)

Figure 4 presents temperature contours at the same z-y plane as above. Considerab asymmetry is observed between the spectators and actors' sides but comfortable levels are maintained on both (16 - 17°C). The maximum temperature at the horizontal cross-section located 5.5 m below the ceiling is 16.7°C as compared with the minimum value of 14°C in the core of the cooling air jet. Near the floor, at the cross-section located 0.75 m above floor the maximum temperature is still 16.8°C.

Figures 5 and 6 present the same information on velocity and temperature, respectively, for the case of Studio 1 with the lights switched off. Similar patterns are observed for both velocity vectors and temperature contours. However, the maxi mum velocity in the studio is now 1.20 m/s as compared with 1.45 m/s when the lights are on; and the maximum temperature has dropped to 15°C as compared with 22°C when the lights are on. Figure 7 presents velocity vectors for this case, from the top view, indicating the flow pattern at the horizontal mid-plane.

Figures 8 to 10 illustrate some of the results for Studio 2. Because of symmetry about the y-z plane, only half of the Studio is studied. Figure 9 presents velocity vectors on the x-z plane passing through the middle of the Studio, while Figs. 10 and 11 depict the temperature contours in the x-z and y-z mid-planes, respectively.

The results reveal that for this Studio the maximum w-velocity is about 1.20 m/s and appears around the middle of the height; and the maximum temperature near the ceiling, is 22°C.

In an effort to obtain velocities of acceptable levels (about 0.3 m/s) in Studio 1, two further designs of the ventilation air inlets were considered. One consists of a single, but enlarged inlet, the second of nine small inlets, as shown in Fig. 11. Figure 12 presents velocity vectors and temperature contours for the large-inlet case, while Figs. 13, 14 and 15 present the same information for the nine-inlet case. For this case, the velocities have diminished to a maximum of 0.3 m/s and comfortable temperature levels are maintained near the floor. It appears clearly that this is the best choice concerning the ventilation arrangement for this Studio

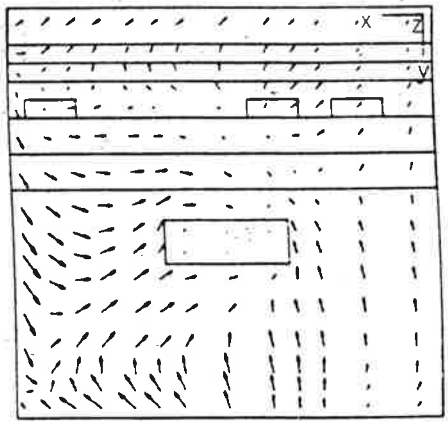



Fig. 7 Velocity vectors on the horizontal x-y plane through the middle of the studio (top view). Lights off.

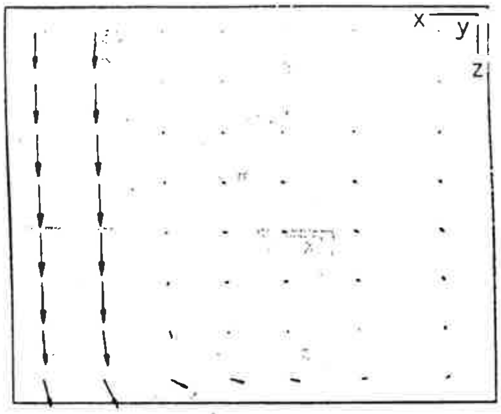



Fig. 8 Velocity vectors on x-z plane through the middle of studio 2

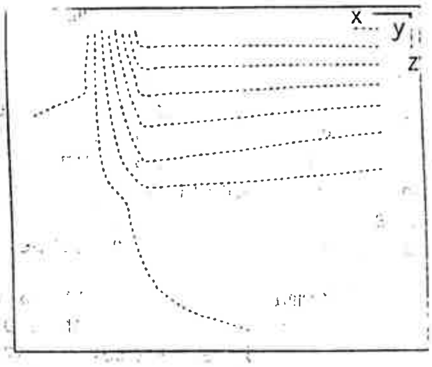



Fig. 9 Temperature contours on a x-z middle-plane (temperature range 287 K to 297 K)

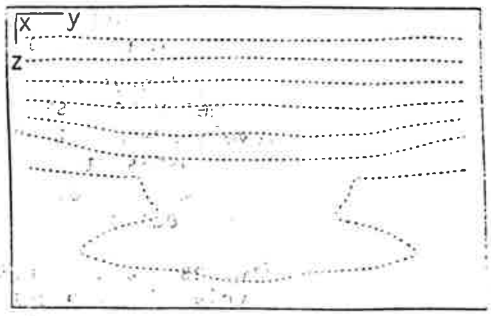



Fig. 10 Temperature contours on y-z middle plane (temperature range 288 K to 295 K)

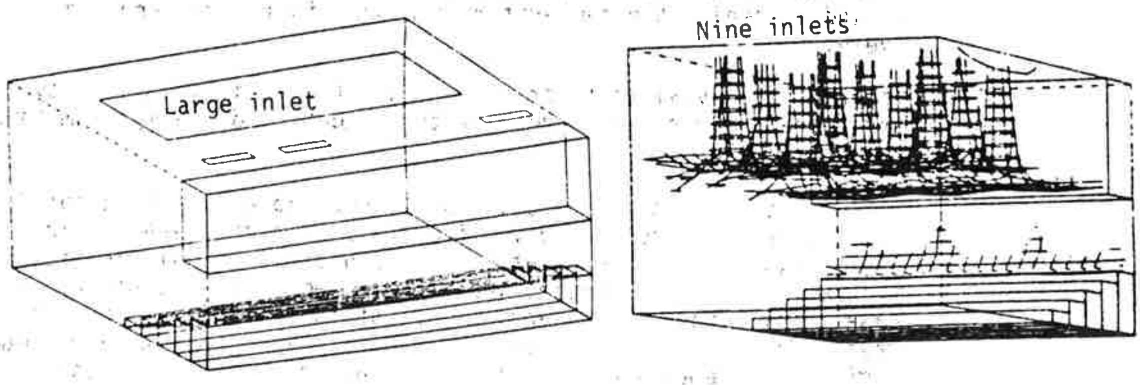
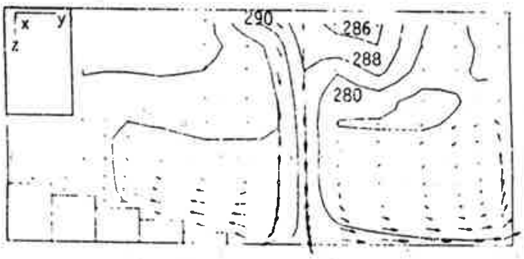
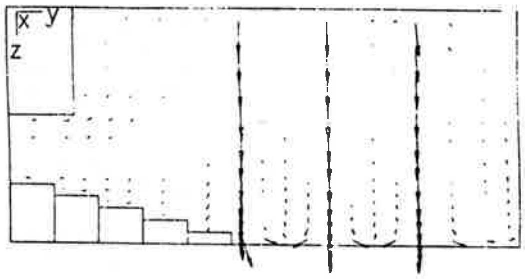



Fig. 11 Enlarged-inlet and nine-inlet configurations



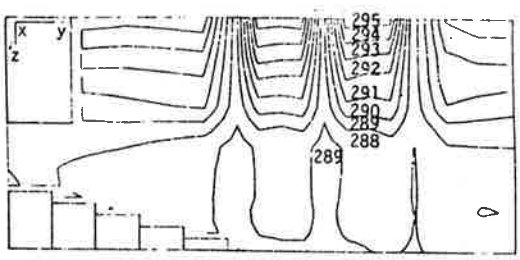

Large-inlet Configuration

Fig. 12 Velocity vectors and temperature contours on the middle z-y plane (max. velocity = 0.8 m/s, temperature range 280 K to 300 K in ten equal intervals)




Nine-inlet Configuration

Fig. 13 Velocity vectors on the middle z-y plane (max. velocity = 0.3 m/s)




Nine-inlet configuration

Fig. 14 Temperature contours on the middle z-y plane (temperature range 285 K to 295 K in ten equal intervals)

## CONCLUSIONS

A computational method has been described, and used to predict flow and temperature distributions in 3D enclosures. The study demonstrated that numerical solutions for practical problems relating to buildings, such as, for example, heating and ventilation, can be obtained quickly and economically. Results have been presented and appear physically plausible. Since no grid-refinement studies were performed, no claim on the quantitative accuracy of the results can be made at present. However, the relative advantages and disadvantages of the various ventilation designs studied are clearly predicted, at least qualitatively. Further work is still required, particularly grid-refinement studies, and comparison of predictions with experimental measurements.

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