An improved viscous fluid elastic registration algorithm of medical images based on parallel computation

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Abstract

Image elastic registration based on the viscous fluid model is time-consuming to solve partial differential equation (PDE) to obtain the velocity and displacement field of the floating image. The method is also sensitive to the gray-scale transformation, with a moving force generated by the gray difference between the two pre-registered images. This paper proposes an improved algorithm which employs the mutual information as a particle moving force, thereby moving the floating image space to obtain the reference image. Conjugate gradient iteration, which is suitable for parallel computing is used to solve the PDE. The proposed registration processing is designed to perform on compute unified device architecture (CUDA) which coordinates CPU and GPU to accomplish concurrent computation. The solution of the PDE is effectively performed on multi-GPU. Experimental results show that the presented method improves the robustness and efficiency of the registration based on the viscous fluid model.

Keywords: Elastic Registration, Viscous Fluid, Mutual Information, Conjugate Gradient Iteration; CUDA

1 Introduction

The purpose of medical image registration is to use geometric transformation to achieve spatial consistency between a reference image and a target image. The corresponding points, corresponding surface and pixel values are found which will obtain the best similarity measure, so that the two images achieve the best matching effect. In computer-aided therapy and image guided radiation therapy, medical image registration is the basis of image fusion and 3D visualization of medical images and is a necessary prerequisite for subsequent processing, image measurement and analysis. The rapid development of computer technology has promoted rapid progress and extensive application of medical image registration technology. An optimization strategy can be used to improve the quality of image registration and elastic image registration will be a hot topic for medical image registration in the future [1].

Large scale nonlinear deformation is produced in medical images due to breathing, posture changes, organ peristalsis and a large number of non-rigid soft tissues in the abdominal cavity and the thoracic cavity, which causes great difficulty for diagnosis and treatment. To some extent, an elastic registration algorithm of medical images can solve this problem and can be used to achieve diagnostic image fusion, contrast and target recognition. However, most of the current elastic registration algorithms are only suitable for small image deformations. The viscous fluid model proposed by E.Christensen can generate large and nonlinear deformations and is suitable for the registration of medical images with large scale deformation of soft tissue [2]. The viscous fluid model using fluid particle motion can simulate random complex deformation characteristics, by simulating the deformation process for fluid flow, enabling registration of the floating image to the target image under the internal forces of fluid. Since solving PDE (Partial Differential Equation) in a viscous fluid model registration may take a very long time, researchers have proposed many methods to accelerate the registration speed. Hartkens [3] combined the characteristic of points and surfaces and gray method to structure a measure of similarity, which can improve the registration speed to some extent. Rong Chengcheng [4] presented a fast registration algorithm of viscous fluid based on a B spline model to speed up the calculation. Tong Ming [5] proposed a registration method using an LBM model, which greatly improves the speed of the fluid registration algorithm.

With the advancement of medical imaging technology, the amount of information contained in a medical image is increasing. Therefore, the methods using viscous fluid registration with a partial differential equation solution take a long time to be completed by the CPU. Specialized GPU (Graphics Processing Units), which have been recently developed, were introduced to the medical image registration algorithm [6-9]. This

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paper proposes a method using GPU which reduces the time taken to solve the PDE equation, with the purpose of improving the speed of the viscous fluid registration algorithm. Meanwhile, MI (Mutual Information) is proposed to replace the gray level difference, the grid division method is for the probability density function and the conjugate gradient method [10] is employed to solve the PDE equation. Experiments show that the method retains registration precision while greatly improving the registration speed.

2 Background theory of fluid viscous elastic registration

Non-rigid registration based on a physical model uses a Eulerian reference frame to describe the deformation field [2]. Long, nonlinear deformation can be described relatively easily in the Eulerian reference frame, since the point deformation continuity can be easily observed using fixed observation points. The frame is suitable for viscous fluid elastic registration. FIGURE 1 shows the Euler displacement field, and describes the deformation process as the floating image point moving to a fixed point in the reference image.

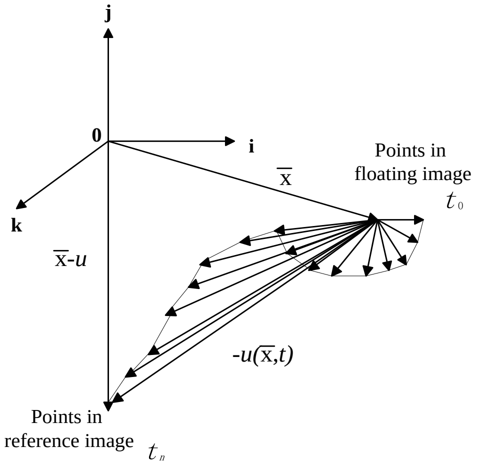


FIGURE 1 Description of the displacement field of the Eulerian reference frame

In the Eulerian reference frame, the relationship between the velocity field v and the displacement field u is described by Equation 1.

$$v_m(\vec{X},t) = \frac{\partial u_m}{\partial t} + \sum_{k=1}^{3} v_k(\vec{X},t)\frac{\partial u_m}{\partial x_k} \quad 1 \le m \le 3 . \tag{1}$$

In this equation, $\sum_{k=1}^{3} v_k(\vec{X},t)\frac{\partial u_m}{\partial x_k}$ is the non-linear movement component of. Without this component, and would have a simple linear relationship.

The deformation process of the image registration based on the fluid model can be described by the Navier-Stokes partial differential equations as follows:

$$\mu\nabla^2 v(x,y,z) + (\lambda+\mu)\nabla(\nabla\times v(x,y,z)) + b(u) = 0 \tag{2}$$

where λ and μ are the viscosity coefficients, ∇^2 is the Laplasse operator, ∇ is the divergence operator, $b(u)$ is the external force.

In order to simplify the calculation, generally the method of finite difference is used to make Equation (2) discrete. Equation (3) shows the discretized PDE equation for the fluid model registration.

$$\begin{cases} \mu(v^1_{i,j+1}, v^1_{i,j-1}, v^1_{i+1,j}, v^1_{i-1,j}, 4v^1_{i,j}) + (\mu+\lambda) \\ (v^1_{i+1,j} + v^1_{i-1,j} - 2v^1_{i,j}) + (\mu+\lambda)(v^2_{i+1,j+1} - \\ v^2_{i-1,j+1} + v^2_{i-1,j-1} - v^2_{i+1,j-1})/4 = \Delta^2 b \\ \mu(v^2_{i,j+1}, v^2_{i,j-1}, v^2_{i+1,j}, v^2_{i-1,j}, 4v^2_{i,j}) + (\mu+\lambda) \\ (v^2_{i+1,j} + v^2_{i-1,j} - 2v^2_{i,j}) + (\mu+\lambda)(v^1_{i+1,j+1} - \\ v^1_{i-1,j+1} + v^1_{i-1,j-1} - v^1_{i+1,j-1})/4 = \Delta^2 b \end{cases} \tag{3}$$

3 Improved viscous fluid registration algorithm

For viscous fluid registration of medical images, an external force is used to match the reference image to the floating image, and the key is to solve the PDE equation (Equation 3), which is generated by the transformation of the Bayesian estimation. Generally, similarity criterion with gray difference is used, and the force of the particle motion is given in Equation (4).

$$f = A_{ij} - B_{ij} \qquad i > 0, j > 0, \tag{4}$$

where A_{ij} is the gray value of point (i,j) of the floating image and B_{ij} is the gray value of point (i,j) of the reference image. However, the method using the gray difference between two images is sensitive. MI is the effective similarity criterion of the images, which can be applied to image registration and can achieve a good match even if part of the image data is damaged. Better registration accuracy and robustness can be obtained by employing similarity criterion based on mutual information with the external force b . Therefore, dissimilarity in the distribution function between the reference image and the floating image produces the force of particle motion as follows:

$$I(r,f) = \sum_r \sum_f P(r,f)(\log P(r,f) - \log P(r)P(f)), \tag{5}$$

$$b(r,f) = I(r,f), \tag{6}$$

where $p(r,f)$ is the function of the joint probability density of the reference image and the floating image, $p(r)$ and $p(f)$ are the edge probability density functions of the reference image and the floating image respectively. When the power $b(r,f)$ is zero in the partial equation, the reference image and the floating image reach local alignment in the space. When the force $b(r,f)$ is zero in the global equation, the reference image and the floating image reach complete alignment.

Combining Equation (5) with Equation (2), a partial differential equation is obtained in the improved algorithm, shown in Equation (7).

$$\mu\nabla^2 v(x,y,z)+(\lambda+\mu)\nabla(\nabla\times v(x,y,z))+ \sum_r\sum_f P(r,f)(\log P(r,f)-\log P(r)P(f))=0 \ . \quad (7)$$

The method of grid division is employed to solve the distribution function of the images and obtain the edge probability density function. Different mesh distribution functions correspond to different grid divisions. Model D2Q9 (D for dimension, Q for the sum of the direction of the particle movement) is the most commonly used method for grid division and obtains the best effects. e_0, e_1,..., e_8 are the nine directions of motion of the particle, as shown in FIGURE 2. The corresponding distribution function is shown in Equation (8).

$$f_a=\rho\omega_a[1+3(e_a\cdot u)+9/2(e_a\cdot u)^2-3/2u^2] \ , \quad (8)$$

where a is the motion of the particle, ω_a =4/9 when a=0, ω_a =1/9 when a =1,2,3,4 and ω_a =1/36 when a =5,6,7,8. $p(r)$ and $p(f)$ are the edge probability density of the reference image and the floating image respectively, which can be obtained by solving the guide function of the distribution function f_a using Equation(9) and (10).

$$P(r)=\sum_r f_r{'}=\sum_r(4\rho/9)(3u-9/e_0^4u^2-3/2u^2) \ , \quad (9)$$

$$P(f)=\sum_f f_f{'}=\sum_f \rho\omega_a(3u-9/e_0^4u^2-3/2u^2) \ , \ a=1,2,\ldots,8 \quad (10)$$

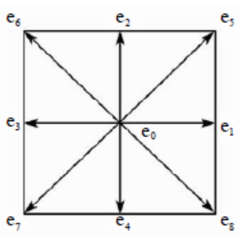


FIGURE 2 Model D2Q9

The successive over-relaxation (SOR) iterative method is usually used for solving the PDE (Equation 3). However, the SOR method is very time-consuming and it is difficult to obtain an optimal relaxation parameter. The conjugate gradient method for solving linear equations [7] need not estimate any parameters, since each iteration calculates the vectors, so it is suitable for parallel computing and operation by the GPU. Therefore, the paper uses the conjugate gradient method for solving the PDE equation based on the iterative formula shown in Equation (11).

$$u_{k+1}=u_k+\alpha_k f_k \qquad k>0 \ , \quad (11)$$

where, u_k is the particle displacement in the K direction, α_k (usually α_k =1) is the factor of the length of step in u_k and f_k is the force of the particle in u_k.

Thus, the viscous fluid registration algorithm of medical images based on GPU is as follows:

1) At t = 0, set the particle displacement field equal to zero, namely $u^1(x,0)=u^2(x,0)=0$; the current iteration number is m and the threshold value is ε when the algorithm is completed.

2) Use equation (4) to calculate the object force b in the GPU.

3) Judge if all the pixels x under force b in the image registration are lower than the preset threshold value, if yes, then stop the cycle.

4) Use the conjugate gradient method (Equation 11) to iteratively solve the partial differential equations (Equation 7) of the viscous fluid registration algorithm to obtain the velocity field.

5) Once the velocity field v is known, use Equation (1) to solve the displacement field u ;

6) Calculate and determine whether the Jacobian of the pixel of the transformed image in current time is less than the threshold value (typically 0.5), if yes, return to 1), else return to 2).

4 The viscous fluid registration algorithm of medical images based on GPU

GPU has been widely used for general calculations due to high memory bandwidth, high parallelism and programmability. Although GPU does not perform as well as CPU when processing complicated instructions, it is very suitable for handling a large number of repetitive and simple parallel computations. Therefore, for simple and large repetitive operation, equation (3), (4) and (6) are very suitable for parallel processing by a GPU. The viscous fluid registration of medical images can be effectively processed using Compute Unified Device Architecture (CUDA), which is designed to coordinate CPU and GPU to accomplish concurrent computation [11-12].

4.1 GENERAL PARALLEL COMPUTING FRAMEWORK: CUDA

CUDA is a general parallel computing framework launched by NVIDIA, and enables GPU to solve complex calculations using programming based on the C language. The key components of CUDA are a hierarchical structure of the thread groups, shared memory and screen synchronization. It provides fine-grained data in parallel and parallel threads which nest in the coarse-grained data and threads in parallel. Complex problems are solved by gradually being broken down into smaller sub-problems for parallel computing. CUDA can realize scalable application models to run on any number of processor cores.

In CUDA architecture, a parallel program can be divided into two parts, the host and the device. When a program is run, the data in the host is copied to the GPU for computing, and then the calculation results are returned to the host. The thread, block and grid are constructed based on the parallel execution model of the CUDA, and the 1D, 2D and 3D thread organization are respectively supported. The thread is the basic unit of the CUDA language.

4.2 VISCOUS FLUID REGISTRATION BASED ON GPU PARALLEL ALGORITHM

The computing program of the viscous fluid registration algorithm of medical image based on GPU mainly contains three kernel functions: Fluidproc(), ConGradient() and Transmit(). Fluidproc() is used to calculate the velocity field of the fluid particle. The data waiting for calculation is arranged firstly along the X direction, then along the Y direction for storage. In the kernel function Fluidproc(), the thread block division is consistent with the order of memory.In the mainstream GPU of NVIDIA, the maximum thread number that can be managed by a thread block is 512. When the target matrix size is greater than 512, every particle cannot correspond to a single thread, so there is therefore a lack of threads. The research chooses 4 x8 threads as a block as shown in FIGURE 3, so that each thread is responsible for handling the particle at the point (i, j) of the velocity field. This block number is $(M/4) \times (N/8)$ with image size of $M \times N$, and each block calculates 4×8 particle velocities.

If the data is only used repeatedly in a single thread, data can be cached to the register; if the data is reused in multiple threads, data can be cached to shared memory. The shared memory caching strategy groups data packets in global memory and then copies the groups to shared memory. In FIGURE 3, threads in same block share memory of the block, and threads in same grid share memory of the grid, to improve the memory access efficiency.

The kernel function ConGradient () is used to iteratively solve the PDE Equation (3). A thread is employed to calculate the displacement of particles in a certain direction k, thus the number of threads is k. Since iterative computation involves many repetitive calculations, the shared memory method is chosen. Using 8×8 threads as a block, the number of blocks is $k/(8\times8)$, and each block can calculate the motion displacement in 64 particle directions.

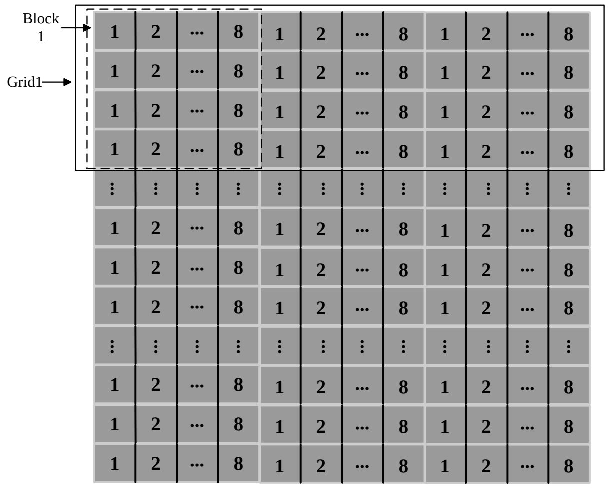


FIGURE 3 Division of the block and grid in Fluidproc()

FIGURE 4 shows the division of blocks and grids in ConGradient().

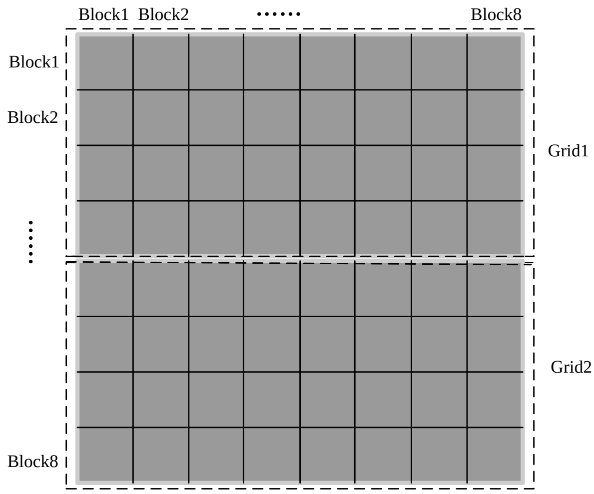


FIGURE 4 Division of blocks and grids in ConGradient()

FIGURE 5 shows the improved viscous fluid registration algorithm of medical images running in the CUDA framework.

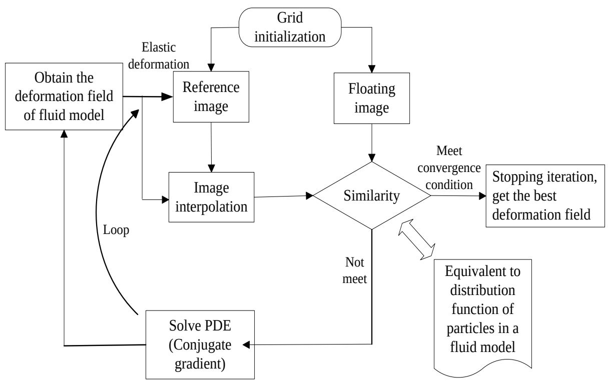
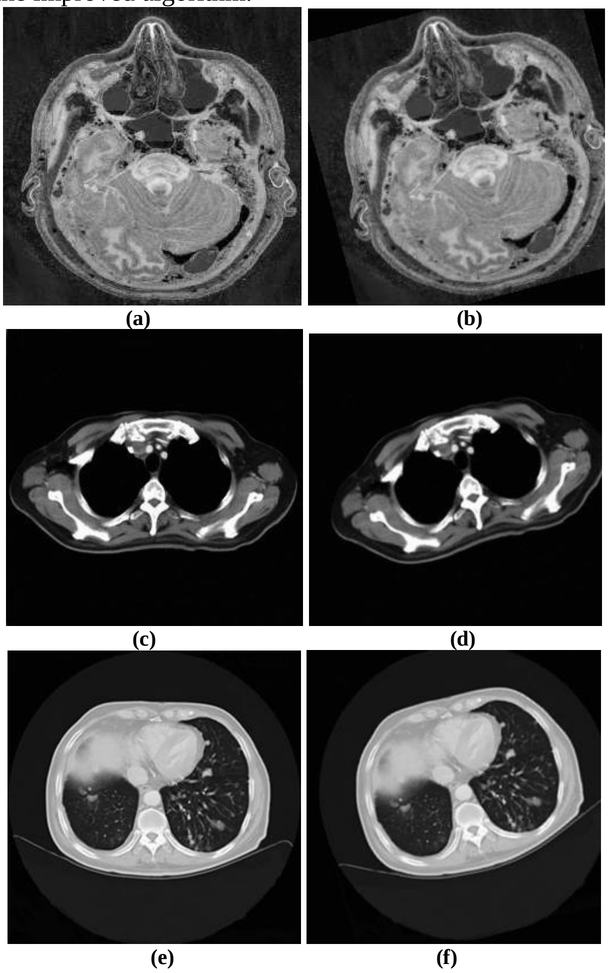


FIGURE 5 Improved viscous fluid registration algorithm of medical images

Firstly, the grids of the reference image and the floating image are initialized at the host, then initialized data is copied to the device to calculate image interpolation and measure the similarity. Finally, the results that meet the threshold are copied to the host.

5 Experimental results

The experimental environment is configured as follows: the operating system is Windows 7; the CPU is Intel (R) Celeron (R) E3300 with frequency of 2.5 GHz, dual core, double thread, memory (RAM) 2.0 GB; the GPU is NVIDIA GeForce GTX 650 TI with 925 MHz core frequency, memory 1 GB, bandwidth 84.6 GB/s; and the compiler is Microsoft Visual Studio 2008. Experimental data uses CT images from different parts of the body. FIGURE 6 shows some experimental cases. Images (a), (c) and (e) in FIGURE 6 are the reference images, and images (b), (d) and (f) are the floating images of (a), (c) and (e) respectively. Images (g), (i) and (k) are the deformation results of (b), (d) and (f) using the traditional viscous fluid registration algorithm, and images (h), (j) and (l) are the corresponding deformation results using the improved algorithm.



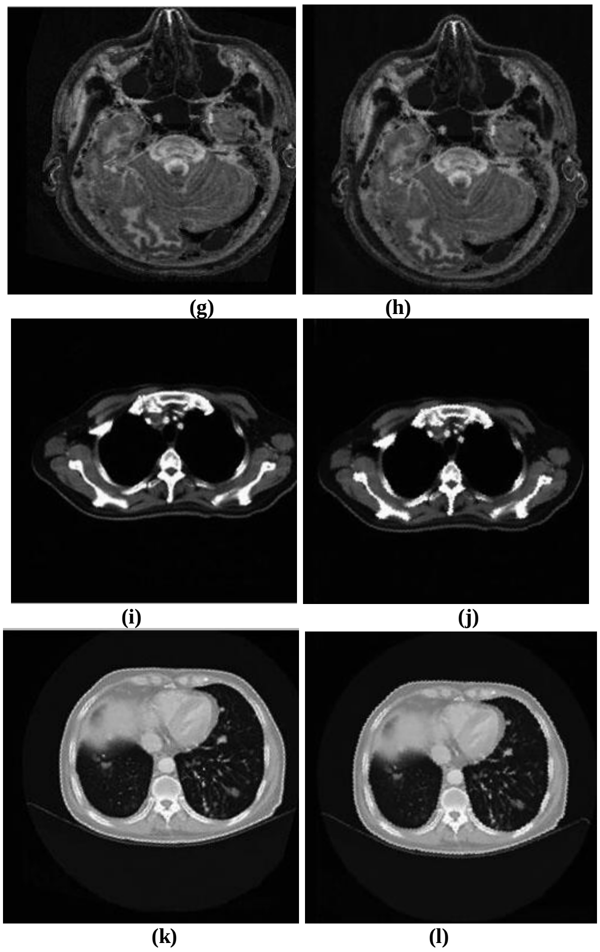


FIGURE 6 Experimental results. (a), (c) and (e) are the reference images, (b), (d) and (f) are the floating images of (a), (c) and (e) respectively, (g), (i) and (k) are deformation results of (b), (d) and (f) using traditional viscous fluid registration algorithm, and (h), (j) and (l) are the corresponding deformation results using the improved algorithm

Table 1 shows the experimental results for different size images based on the traditional viscous fluid registration algorithm. Experimental results for the corresponding images based on the improved registration algorithm on the CPU and on the CUDA are compared in TABLE 2. The results show that in comparison with the traditional viscous fluid registration algorithm, the proposed algorithm not only keeps the original registration accuracy, but improves the speed of the image registration and improves the speed further on the CUDA.

Table 2 also shows that GPU acceleration ratio increases significantly as the image resolution or the amount of images increases.

TABLE 1 Experimental data statistics of the traditional viscous fluid registration algorithm for medical imags

Size of image	MI	Time(ms)	Registration parameters (X,Y)
147×147	1.061	870.68	(-32.753,-34.086)
257×221	4.137	2796.01	(-12.95,-16.05)
256×256	3.151	3152.67	(-3.32,3.63)
512×512	2.676	8838.82	(-6.788,7.189)
1024×1024	2.291	59267.61	(-13.945,15.081)

TABLE 2 Comparison on CPU and on GPU based on the improved algorithm

Size of image	MI	CPU Time(ms)	CUDA Time(ms)	Speed Ratio
147×147	1.053	472.77	42.52	11.1
257×221	4.144	1801.88	110.13	16.4
256×256	3.126	2265.58	126.52	17.9
512×512	2.682	5837.80	185.77	31.4
1024×1024	2.295	38746.72	371.42	104.3

The above experiments show that the proposed method not only maintains the accuracy of registration but also improves the registration speed.

6 Conclusions

Research shows that the image registration algorithm based on the viscous fluid model is very suitable for large scale, complex deformation registrations. However, when the image data is large, this method is very time consuming. To improve the speed and the precision of the algorithm, the paper proposes an improved method which uses MI to replace the gray difference for external forces. The proposed method is performed on CUDA. Experiments compared the traditional viscous fluid registration algorithm and the improved method. The results illustrated that the presented method achieved better precision and improved the speed significantly. Particularly for larger images, the method can show greater improvements i.e. for images of 1024×1024, the speed ratio reaches 104.3. The algorithm is suitable for all types of large scale deformation images

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