Solar cell as wings of different sizes for flapping-wing micro air vehicles

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Abstract
Currently, the biggest challenge for flapping-wing micro air vehicles is their very short flight duration due to limited on-board energy storage capacity. To overcome this challenge, a concept of solar-cell-flapping-wing micro air vehicle is herein proposed and studied. Thirty-three types of currently successful flapping-wing micro air vehicles (including insect-like, bird-like, and hummingbird-like flapping-wing micro air vehicles) are analyzed to explore scaling laws of flapping-wing micro air vehicles. The influences of wingspan, wing area, flapping frequency, and power on mass of flapping-wing micro air vehicles are studied. A dynamic energy harvesting model of solar-cell-flapping-wing is built up and utilized to formulate energy supply rate equations of three types of flapping-wing micro air vehicles. Considering the averaged ground solar spectral irradiance and today’s energy conversion efficiency of solar cells, the variation of energy supply rate by scales is analyzed. Several critical parameters to design an efficient long duration flapping-wing micro air vehicle are suggested.

Keywords
Flapping-wing, micro air vehicles, scaling law, solar cell, energy supply rate, flight duration

Introduction
Flapping-wing micro air vehicles (FWMAVs) are developed based on the bionic principles of birds and insects. Compared to the fixed-wing and rotary-wing air vehicles, FWMAVs have many advantages and are promising for future. By integrating the power system into a pair of wings, it is possible to tailor their flight characteristics to meet the aerodynamic demands. An insect-like FWMAV is flexible and stable for many complicated tasks. As motors, battery, and control technology have been improved in recent years, bird-like FWMAVs are coming to be closer to their biological sample.¹,²

One of the biggest challenges in today’s FWMAV design is the energy required for a long time flight. Harvard University has developed an insect-size FWMAV with a weight of 60 mg.³ It needs wires to provide external energy for long-term flight. Delft University of Technology has developed DelFly Micro that weighs 3.07 g.⁴ It flies up to 3 min with a 30 mAh battery. AeroVironment Company’s newest Nano Hummingbird has a 19 g mass and 4 min hovering duration.⁵ To achieve a long-term flight, an FWMAV needs stronger battery capacity, more efficient mechanical transmission, and more active deformation wing. Among these, stronger battery capacity would be most valuable.

Not only FWMAVs face the problem of short flight duration, but many aerial vehicles have the same problem as well. For a fixed wing air vehicle, a solution to improve this difficulty significantly is the use of solar energy. In 2003, AeroVironment constructed Helios with a 75 m wing span. This solar-cell and fuel-cell powered unmanned aerial vehicle demonstrated endurance of 24 h until structural failure.⁶ In 2004, Swiss Federal Institute of Technology Lausanne launched the Sky-Sailor project; this solar energy aircraft can achieve continuous flight at a constant altitude over 24 h using only solar energy.⁷ In 2009, University of Toulouse tested a 500 mm Solar-Storm prototype that

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was covered with 20 solar tiles. It achieved an endurance of 90 min. On average, 40% of the total power is obtained from the solar cells during the flight.\textsuperscript{8} In 2010, DARPA funded the Boeing Solar Eagle project, which aims at staying aloft for up to five years at altitudes above 60,000 feet.\textsuperscript{9} Although these given examples are all fixed wing versions, they show us a great potential that solar cell could be an effective means to increase flight duration of aircraft vehicles.

Although a small size, lightweight, high energy density battery is expected, the currently used batteries, such as storage battery, disposable chemical battery, and fuel cells are not satisfactory for micro air vehicle in a short period. Thus, a new concept is needed to increase the potable energy of an FWMAV under the current technology level. In 2015, researchers from the University of Maryland attached solar cells to the wings of Robo Raven III.\textsuperscript{10,11} In the current researchable articles, this may be a first attempt of using solar cells in FWMAVs. As a result, a 10.2% and 18.7% increase in operational time of Robo Raven III were observed with 12 and 22 solar cell modules, respectively. This inspired us to consider the possibility of a solar cell winged FWMAVs. Without adding extra weight, solar cells maybe the choice to be wings of an FWMAV for a longer flight time. In this paper, FWMAVs with solar cell wings are studied. Thirty-three types of insect-like and bird-like developed FWMAVs are involved here to find scaling laws of the realized FWMAVs for the purpose of using solar cells. Based on that, the flapping-wing dynamic model is proposed to evaluate energy supply rate of solar cells as the wings of FWMAVs. Also, the influences of parameters like mass, wingspan, and flapping frequency on the energy efficiency of FWMAVs are analyzed. Several solutions are proposed to design solar cell wing FWMAVs.

**FWMAV scaling law**

Although there is a long history of studying flying principles of insects and birds, it is a hard and different problem to manufacture a flying robot that flies like insects or birds. There are many works discussing scaling laws of insects and birds in biological field. Also, many FWMAVs have been designed and studied based on biological results. In the past 20 years, researches on FWMAV have achieved greatly the development of new materials, new designs, new energy technology, and new findings of biology. Many different FWMAVs have been constructed. Bats, insects, and birds have acted as inspirational sources. Most of FWMAVs can be defined as insect-like FWMAV or bird-like FWMAV (including hummingbird-like FWMAV, a special type of bird-like FWMAV). Because bat-like FWMAV is rare, scaling laws of insect-like and bird-like FWMAVs are discussed here. For manufacturing purpose, scaling laws of FWMAVs would be more helpful than the ones of real insects and birds. However, they are rarely studied until now since they involve more factors.

**Insect-like FWMAV**

Table 1 lists 20 types of representative successfully developed insect-like FWMAVs and their parameters. These FWMAVs are constructed according to the flight mechanisms of insects and have some characteristics similar to insects, such as the size of insects, the method of flapping wings to get high lift and thrust.

To design an FWMAV, a wingspan and wing area parameter is important to a known mass. In Table 1, 20 FWMAVs are listed. As biologists have done in studying insects and birds, a power function is used here to express the relationship between body mass and other parameters (see Figure 1).

As shown in Figure 1, relationships between insect-like FWMAVs mass and wingspan, wing area have regularities if we consider most of the existing FWMAVs. Thus, scaling relations of wingspan \(b\) and wing area \(S\) by mass \(m\) can be written as follows.

\[
b = 3.93m^{0.703} \tag{1}
\]

\[
S = 10.33m^{0.886} \tag{2}
\]

The relation between mass and flapping frequency of natural insects has been expressed as \(f = 28.7m^{-1/3}\) by Azuma.\textsuperscript{32} In Figure 2(a), Azuma’s curve (in solid line) is compared to the power function fitting curve (in dotted line) that was built up by the parameters of insect-like FWMAVs. It is shown that the flapping frequency of the natural insect is always lower than the ones of man-made FWMAVs considering a same mass value. This is mainly due to different lift mechanism. To fly efficiently, insects bend and twist their wings instead of flapping only. However, increasing flapping frequency is the most realistic and simplest way to get sufficient lift of an FWMAV. Kawamura et al.\textsuperscript{33} investigated thrust generation in hovering flight from three types of wings. The results showed that thrust increases with increasing flapping frequency. Lin et al.\textsuperscript{34} also took several experimental tests and demonstrated that lift force increases with increasing flapping frequency under the corresponding flying speed. Many efficient ways through which insects fly, such as when and how to change the shape of wings and angle of attack for airflow change, are still unknown. Thus, the flapping frequency of an FWMAV should be generally higher than an equally weighted insect to realize flying. Also, there are two FWMAVs: Butterfly and Delaware have lower frequency than Azuma’s curve. This is due to bigger wing areas to achieve enough lift.
The relationship between mass and flapping frequency of FWMAVs (solid line in Figure 2(a)) can be described as a power function as

\[ f = 44.63m^{-0.3837} \]  

(3)

The energy consumption of the discussed FWMAVs is shown in Figure 2(b). No clear distribution is shown in the figure about the relationship between mass and power. The current FWMAVs utilized different actuators, types, and aerodynamic layout without unified...
optimization rules. Since we have not found a method to design an energy-saving FWMAV as yet, there is no universal standard to evaluate FWMAVs’ energy consumption in different scales. Thus, we may be far away from a clear understanding of the relation between energy consumption and structure of FWMAVs. Still, a successfully developed FWMAV could be a reference to similar scale designs.

Bird-like FWMAVs

Bird-like FWMAVs are designed and fabricated according to the flight mechanisms of birds. Ten types of representative bird-like FWMAVs and their parameters are listed in Table 2. Compared to the insect-like FWMAVs, bird-like FWMAVs generally have bigger weight, wing span, and wing area with a lower flapping frequency.

According to bird-like FWMAVs’ data in Table 2, the fitting power functions of bird-like FWMAVs’ wingspan $b$ and wing area $S$ by mass $m$ are

$$b = 9.26 m^{0.4457} \quad (4)$$

$$S = 82.75 m^{0.51} \quad (5)$$

As indicated in Table 3, natural birds’ flight parameters are expressed by Shyy et al., including the
smallest bird in the world – hummingbirds. Hummingbird was found to obey an obvious different scaling law than the rest of the birds. It is discussed in the next section.

In Figure 3, bird-like FWMAVs’ wingspan and wing area are compared to that of birds’, according to Tables 2 and 3, and equations (4) and (5). It is found that the wingspan and wing area of bird-like FWMAVs are always bigger than the birds’. This implies that FWMAVs need bigger dimensions to achieve equal lift of birds in the same weight. According to Table 3, a heavier bird-like FWMAV usually has a bigger wingspan and wing area. Yang et al.38 had made two types of flapping wings to test the lift force in a small wind-tunnel, and found that wing with areas 108.75 cm² has a bigger lift force than the case of 64.50 cm².

According to the data of Tables 2 and 3, bird-like FWMAVs’ flapping frequency and power consumption are compared to birds as shown in Figure 4.

Unlike insect-like FWMAVs, as shown in Figure 4(a), the flapping frequency of bird-like FWMAV becomes lower than that of bird’s if mass is larger than a certain value. This does not mean that FWMAV is more efficient than the bird of equal weight. Since increasing of bird’s mass is quicker than that of insects’, the corresponding increasing of wing area is a major factor for lift. High flapping frequency is not an option for larger bird-like FWMAV since their bones cannot afford the stresses that imposed upon by flapping such a large inertial load. On the contrary, smaller FWMAVs can flap at a higher frequency due to their significantly reduced inertial loading. Hence, birds-like FWMAVs mainly increase their lifts through raising wing area but flapping frequency of vehicles. Also, a fitting power function flapping frequency by mass is achieved as

\[
f = 51.79 m^{-0.5045}
\]

Figure 4(b) shows the power consumption of bird-like FWMAVs. They also have no certain rule of distribution, similar to insect-like FWMAVs as shown in Figure 2(b). Interestingly, the power consumption of all the investigated bird-like FWMAVs is lower than their natural counterparts according to Shyy et al.’s equation which is based on steady aerodynamics. This may have two possible explanations. Either man-made robotic birds borrowed some advanced technologies from fixed-wing or rotary-wing. Or, a wrong theory is used

| Animal groups          | Wingspan (cm) | Flapping frequency (Hz) | Wing area (cm²) | Minimum power (W) |
|------------------------|---------------|-------------------------|----------------|-------------------|
| All birds              | –             | 37.82 m⁻⁰.³³            | –              | 2.93 m⁻⁰.¹⁹      |
| All birds except       | 7.91 m⁻⁰.³⁹   | 25.70 m⁻⁰.²⁷            | 11.07 m⁻⁰.⁷²   | –                |
| hummingbirds           |               | –                       |                |                   |
| Hummingbirds           | 5.76 m⁻⁰.⁵³   | 83.29 m⁻⁰.⁶⁰            | 5.23 m⁻¹⁰.⁴⁵   | –                |

Figure 3. Relationship between bird-like FWMAVs’ mass and wingspan, wing area.
to explain flapping wing’s flight. Recent theoretical analysis and experimental studies reveal that birds and insects can produce high lift through the theory of unsteady aerodynamics. So do FWMAVs. Besides, flying animals own the abilities to change shape and sizes of the wing to maximize aerodynamic efficiency. A more efficient FWMAV is expectable when the flight theory of flapping wing is well developed in the future. Thus, FWMAVs may have more means to improve (or adjust) their energy efficiency than equally weighted fixed wing or rotary-wing air vehicles if their working principles are well understood.

**Hummingbird-like FWMAV**

Unlike most of the larger birds that are usually not able to hover, hummingbirds could hover with fully extended wings during the entire wing beat cycle. While hovering, the body axis is inclined towards the horizontal plane and the wing movements describe a figure of a lying eight in the vertical plane. For birds other than hummingbirds, which are not able to rotate their wings, these birds flex their wings during the upstroke.

Nano Hummingbird maybe the most successful hummingbird-like FWMAV ever. It was designed and manufactured by AeroVironment in 2011. It can perform a controlled hovering flight strictly with two flapping wings for about 4 min. An earlier try by AeroVironment is Saturn, a hummingbird-like FWMAV, that can fly for 11 min. The University of Toronto also designed a hummingbird-like FWMAV with four wings. Three different hummingbird-like FWMAV parameters and their calculated parameters based on scaling law are listed in Table 4.

According to Table 4, the wingspan, wing area, and power of each hummingbird-like FWMAV are all greater than its calculated values (based on scaling law), except the flapping frequency. This implies that raising flapping frequency is the most realistic way to realize enough lift and thrust while keeping size as small as possible to simulate natural hummingbirds.

Humming-birds are peculiar flying species with their weights varying among other birds and insects. They have a quite different flying manner than others. In a few successful hummingbird-like FWMAVs, the driving system is always complicated to simulate their natural counterparts. Thus, its controllability is a problem. Also, their power consumption needs to be further studied since there are no sufficient samples and data of hummingbird-like FWMAV and their natural counterparts.

**Energy analysis of solar cell wing**

*An energy harvesting model of solar cell wing*

Continuous progress in solar cell makes us believe that lightweight flexible solar cells can replace the traditional material to fabricate flapping wing for a longer flight duration without increasing the weight of FWMAV. According to the most recent work by Bulović and colleagues, an ultra-thin, lightweight organic solar cell is fabricated and recorded as the thinnest (1.3 μm) and lightest (3.6 g/m²) solar cell. It is even lighter than nanopaper, a promising material for flapping wing with areal density of 4.5 g/m² to substituting current PVC(1.38 g/cm³) or polyester (2.06 g/m²) material. This is a significant progress considering the areal density (from 936 to 2062 g/m²) of the current commercial solar cells. Since its density is reducing and coming
close to current flapping wing’s materials, the mass difference between solar cell and current material is ignored in this paper. That is to say, the areal density of applied solar cell here is regarded as the same as the current flapping wing’s material.

According to its definition by World Meteorological Organization, the solar spectral irradiance \( I_{sc} \) is 1367 W/m\(^2\) with changes by some factors, such as geographic position, time, solar panels orientation, and albedo.\(^5\) Considering cloud and atmosphere, the average irradiance of direct solar radiation on the ground \( I_{d} \) is 170 W/m\(^2\), one-sixth of \( I_{sc} \) under standard condition.\(^5\) Since a solar cell flapping wing of FWMAV is in motion, rate of energy harvesting by a solar flapping wing is variant by its projection area to solar light. In Figure 5, a direct solar radiation to a solar cell flapping wing is presented.

If the direction of solar spectral irradiance is assumed unchanged and parallel to the symmetry plane \( O_1O_2 \) of the FWMAV, rate of energy harvesting can be calculated, considering flapping angle between two extreme positions as \( (\alpha + \beta) \) and a vertical solar radiation to the surface of solar cells as \( I_n \). The solar spectral irradiance \( I \) in any flapping angle \( \theta \) is calculated as

\[
I = I_n \cos \theta \tag{7}
\]

Then, the average solar radiation in one flapping cycle period can be expressed as follows

\[
I_a = \frac{1}{\alpha + \beta} \int_{-\beta}^{\alpha} I_n \cos \theta d\theta = \frac{\sin \alpha + \sin \beta}{\alpha + \beta} I_n \tag{8}
\]

To keep concision and clarity of the proposed model, it is assumed that the irradiance of direct solar radiation to flapping wings’ symmetry plane is a constant and equals to \( I_n \). The unchanged value \( I_n \) is applied here to delegate a fixed light condition, no matter how different the time, the vehicle type, the flying orientation and the geographic position are between samples.

A more accurate energy harvesting model would be achieved if a function is used to substitute \( I_n \) into equation (8) considering a specific value, a specific position, a detailed time, a known solar cell flapping wing orientation, etc. But, this would make energy harvesting model more complex. In addition, energy comparison of different types of FWMAVs would be more difficult. Hence, a concise model is decided to be used here to concentrate the study on scaling laws of FWMAVs for their feasibility analysis.

A suitable solar cell as wings of FWMAV needs to meet two basic requirements: good anti-fatigue performance that can flap hundred thousand times and a very light weight that can decrease the self-weight of an FWMAV. Indeed, solar cell production has been gaining momentum in recent years. In 2011, Kaltenbrunner\(^5\) demonstrated a ultra-thin and lightweight organic solar cell with high flexibility; the total thickness was only 1.4-μm-thick which is less than a typical thread of spider silk. In 2015, Kim et al.\(^5\) researched on a flexible perovskite solar cell exhibiting 12.2% power conversion efficiency, and it could maintain 95% of the initial conversion efficiency after 1000 bending cycles for a bending radius of 10 mm. These progresses make flexible,

### Table 4. Hummingbird-like FWMAVs.

| Number | Project name or unit | Mass (g) | Wingspan (cm) | Wing area (cm\(^2\)) | Flapping frequency (Hz) | Power (W) |
|--------|----------------------|----------|---------------|-----------------------|------------------------|-----------|
| 31     | Saturn\(^5\)         | 17.5     | 15.8          | –                     | 27.5                   | 3.27      |
| 31     | Saturn (calculate)   | 17.5     | 26.25         | 102.62                | 14.95                  | 5.05      |
| 32     | Nano Hummingbird\(^5\) | 19.0    | 16.5          | –                     | 30                     | –         |
| 32     | Nano Hummingbird (calculate) | 19.0 | 27.43         | 111.79                | 14.23                  | 5.12      |
| 33     | Mentor\(^49\)        | 10       | 7.5           | 44.2                  | 80                     | 0.6       |
| 33     | Mentor (calculate)   | 10       | 19.5          | 57.35                 | 20.92                  | 4.53      |

FWMAVs: flapping-wing micro air vehicles.

Note: ‘–’ unknown value.

![Figure 5. A solar radiation model of solar cell flapping wings.](image)
lightweight, and durable solar-cell-flapping-wing expectable. In this paper, it is assumed that we have that type of solar cells for fabrication of flapping wings.

Energy analysis of a solar cell FWMAV

The classic fruit fly Drosophila virilis has been found with a 29 W/kg body-mass-specific power and 17% muscle efficiency by Sun.\(^5^6\) In the following discussion, Sun’s result is regarded as the minimum requirement, \(P_{\text{min}}\), of an insect-like FWMAV. Energy supply rate, a quantity description of the energy harvest by solar cell wings vs. the minimum power requirement of an FWMAV, is defined here as a percent value. Considering equations (2) and (5), and Table 3, the energy supply rate of insect-like, bird-like, and hummingbird-like FWMAV with solar cell flapping wings should be expressed as follows

\[
\eta_1 = \frac{I_a S \eta_e}{P_{\text{min}}} = 0.0356 m^{-0.114} \frac{\sin \alpha + \sin \beta}{\alpha + \beta} I_a \eta_e \tag{9}
\]

\[
\eta_2 = \frac{I_a S \eta_e}{P_{\text{min}}} = 0.0028 m^{0.32} \frac{\sin \alpha + \sin \beta}{\alpha + \beta} I_a \eta_e \tag{10}
\]

\[
\eta_3 = \frac{I_a S \eta_e}{P_{\text{min}}} = 0.0001785 m^{0.85} \frac{\sin \alpha + \sin \beta}{\alpha + \beta} I_a \eta_e \tag{11}
\]

where \(\eta_e\) is the energy conversion efficiency of solar cell. Equations (9) to (11) imply that the energy supply rate relies mainly on three parameters: weight, solar spectral irradiance, and energy conversion rate of solar cell. Previous researches\(^5^7,5^8\) have found that most of flying animals have a flapping range of \(\alpha + \beta\) is 120°, and energy conversion efficiency could be 10% to 40%, energy supply rate of three kinds FWMAV are drawn in Figure 6.

The energy supply rate of insect-like FWMAV is shown in Figure 6, which shows an inverse relation to the weight. Energy supply rate sharply changes in the range of 0–1 g and decreases slowly to a limit as the weight increased. In Figure 6(b), the energy supply rate of bird-like FWMAV increases exponentially by increasing of weight, while the energy supply rate of hummingbird-like FWMAV seems to be linear. As it can be seen, there exists a tipping point around 183 g. If the weight is smaller than 183 g, a bird-like FWMAV has better energy supply rate than a hummingbird-like FWMAV with solar cell wings. Otherwise, a hummingbird-like FWMAV is a better choice to harvest energy by solar cell wings.

According to equations (1) to (6), FWMAVs’ wing-span, wing area, and flapping frequency are all power functions of weight. A further study is executed to explore the influences of wingspan, wing area, and flapping frequency to energy supply rate (see Figure 7). Figure 7(a), (c), and (e) discusses insect-like FWMAVs while other figures discuss rest of the two kinds of FWMAVs.

According to Figure 7(a) and (c), the energy supply rate of insect-like FWMAVs relates inversely to wing-span and wing area, just like Figure 6(a). Energy supply rate decreases sharply in the beginning and decreases slowly in the later when wingspan and wing area increase. With regard to the other two kinds of FWMAVs, Figure 7(b) and (d) shows similar trend as Figure 6(b) does. Energy supply rate of bird-like FWMAVs is better than hummingbird-like FWMAVs as the wingspan is less than 95 cm or wing area is

![Figure 6. Relationship between FWMAV energy supply rate and mass.](image-url)
Figure 7. Relationship between FWMAV energy supply rate and wingspan, wing area, flapping frequency.
less than 1180 cm$^2$. Otherwise, hummingbird-like FWMAVs perform better.

The influences of flapping frequency on energy supply rate are shown in Figure 7(e) and (f) for insect-like FWMAVs and bird-like FWMAVs separately. In insect-like FWMAVs, the energy supply rate rises slowly with increase of flapping frequency. In bird-like FWMAVs, the energy supply rate decreases rapidly at first and then decreases slowly when increasing flapping frequency.

The theoretical limit of solar cell’s energy conversion efficiency is 93.3%, whereas the current technological level reaches about 10–30%. If solar spectral irradiance is a constant, there is a linear relationship between energy supply rate and solar cell’s energy conversion efficiency. Thus, a solar cell with high energy conversion efficiency and long fatigue service life could raise feasibility of our hope to realize a solar cell FWMAV. It would be a good way to achieve long-term autonomous flying.

Conclusions

To explore scaling laws of FWMAVs, thirty-three types of currently representative FWMAVs are analyzed according to three types of classes: insect-like, bird-like, and hummingbird-like FWMAVs. With the power function fitting, relations of parameters to weight of FWMAVs are studied and discussed to understand the main reasons for a man-made flapping fly.

To overcome the challenge of short flight duration, an idea has been proposed in this paper, which is to let the flapping wings made of solar cells. Based on achieved scaling laws, a prolonging index of flight duration, energy supply rate, is given out considering utilization of solar cell flapping wings. Under the current technological level and environment parameters, the energy supply rate is calculated and shown in different weights of three types of FWMAVs. Results show that insect-like FWMAV has a higher energy supply rate when weight is less than 1 g, energy supply rate of hummingbird-like FWMAV is better than bird-like FWMAV when weight is above 183 g. Also, wingspan, wing area, and flapping frequency are discussed to discover their influences on energy supply rate. It is found that, for insect-like FWMAVs, the energy supply rate decreases with the increase of wingspan and wing area, whereas the flapping frequency has opposite effect. Energy supply rate of hummingbird-like FWMAVs is better than bird-like FWMAVs as the wingspan is bigger than 95 cm or wing area larger than 1180 cm$^2$. Unlike insect-like FWMAVs, the energy supply rate of both bird-like and hummingbird-like FWMAVs decreases as the flapping frequency increases.

As this paper is peer-reviewed, a further test is reported by researchers from University of Maryland on their work of attaching solar cells on flapping wings. Also, solar cell has been fabricated in a smaller width and weight by an MIT team. The proposed model tool discussed in this paper would come earlier than it is predicted.

According to the abovementioned results, a solar-cell-FWMAV is feasible to supply a longer flight duration than the traditional one. Even more, realization of this idea is getting closer and closer. With the achieved data in this paper, it is possible to design an FWMAV that could fly longer, which is our future work.

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